EVALUATION OF THE NUTRIENT REMOVAL EFFICIENCY OF A CONSTRUCTED WETLAND SYSTEM

A Thesis

by

KIMBERLY ANN HART

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2006

Major Subject: Forestry

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Approved by:

Chair of Committee,	Raghavan Srinivasan
Committee Members,	Stephen Davis
	Robert Knight
Head of Department,	Steven Whisenant

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ABSTRACT

Evaluation of the Nutrient Removal Efficiency of a Constructed Wetland System.

(August 2006)

Kimberly Ann Hart, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Raghavan Srinivasan

In north central Texas, USA, free-water surface wetlands have been constructed to treat pre-treated wastewater effluent from the Trinity River. Water quality and vegetation data from the first two years of operation (June 2003 to May 2005) were used to determine cell-to-cell and system-wide removal efficiency of total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN). The wetland system consisted of one non-vegetated sedimentation basin and a series of four connected, vegetated wetland cells. Temporal analyses displayed varying monthly, seasonal and yearly trends of the wetlands' concentration of the three parameters. Spatial analysis results confirmed that TSS, TP and TN concentrations were greater at the beginning of the system as compared to the end of the wetland system. Percent reduction analyses showed that the second wetland cell (WC2) was the most efficient in TSS, TP and TN removal, while the last wetland cell (WC4) had the lowest reduction of the three parameters. TSS removal was significant ($\alpha = 0.05$) moving consecutively among the sites in the wetland system, with exception to the last wetland cell. TP removal was only significant ($\alpha = 0.05$) moving from the third wetland cell (WC3) to WC4, while TN removal was significant ($\alpha = 0.05$) moving from the sedimentation basin to the first wetland cell (WC1) and then again moving from WC3 to WC4. Overall removal efficiency of the wetland system (from the Trinity River to WC4) was quite high, with reductions over 97% for TSS, 47% for TP and 67% for TN. N:P ratios decreased moving consecutively throughout the field-scale wetlands. Vegetation analyses found WCs 1 and 3 to contain the greatest vegetation species richness, while WC2 had the lowest richness. The vegetative composition of the four cells was mostly the same. A comparison was conducted between the nutrient reduction efficiency and vegetation data of this wetland system with data from a pilot-scale wetland system that was operated from 1992 to 2000. The findings of this study suggest that during the first two years of operation, the wetland system's performance is comparable to the pilot-scale wetlands which were operated for eight years.

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NOMENCLATURE

AC	Alligator Creek
ALK	Alkalinity
APAI	Alan Plummer Associates, Inc.
CHLOR	Chlorophyll *a*
COND	Conductivity
DO	Dissolved Oxygen
HARD	Hardness
NH3	Ammonia
NOX	Nitrate and Nitrite
OP	Organic Phosphorus
PS	Pump Station
SB	Sedimentation Basin
TEMP	Water Temperature
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TPWD	Texas Parks and Wildlife
TRWD	Tarrant Regional Water District
TSS	Total Suspended Solids
TURB	Turbidity
TVSS	Total Volatile Suspended Solids
WC1	Wetland Cell 1
WC2	Wetland Cell 2
WC3	Wetland Cell 3
WC4	Wetland Cell 4

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I. INTRODUCTION

Concerns over water quantity and quality have steadily increased across the United States primarily because of the growth in the nation's population. Growing populations yield greater pressure on existing water supplies and often generate demand for development of additional sources of water. In Texas, the population is estimated to increase by 90% over a 50-yr period (2000 to 2050), while the State's water demand is projected to increase by 67% (TWDB 2002). According to such predictions, there is concern that Texas' water supply will eventually decline to the point where water demands can no longer be met (Conner and James 1996).

To preserve and supplement existing water resources, a state-wide water plan (Senate Bill 1) was developed to meet Texas' water demands. The 2002 State Water Plan is a comprehensive, long-term, 50-yr plan designed to identify supply and demand strategies to meet future water needs (TWDB 2002). The Plan works from a bottom-up approach, where 16 separate regions each submit a regional plan that discusses the water supply/demand issues that are specific to that region of Texas. Each regional plan addresses water management strategies to conserve water supplies, meet future water supply needs and respond to future droughts in the planning areas (TWDB 2002).

This study focused on a particular water management strategy that has been implemented in Region C, a 16-county area in north central Texas. The Tarrant Regional Water District (TRWD), one of the major water providers in Region C, identified and evaluated several options in developing a long-range water supply that would meet the projected needs for the region. In the past, a newly constructed reservoir would have sufficed as the means for a new water supply; however, time and cost constraints, along with water rights and habitat loss issues were all heavily considered and it was determined that another solution was needed. TRWD proposed the idea of supplementing their existing drinking water supplies with an available water source.

This thesis follows the style and format of *Wetlands.*

TRWD decided that diverting water from the Trinity River into two of the District's existing reservoirs would be the most viable option. The Trinity River, which runs directly through several different cities, including Dallas and Fort Worth, receives a large amount of treated wastewater effluent. TRWD realized that in order to reuse/recycle the water diverted from the Trinity River, additional treatment was necessary before the water could be put into the existing reservoirs. After evaluating several secondary treatment options, TRWD concluded that using a series of constructed wetlands to polish the pretreated wastewater would provide the water quality levels they needed to obtain.

TRWD initiated their water reuse project with the development of a pilot constructed wetland system. TRWD operated and tested the pilot-scale wetlands for eight years. At the end of the pilot-scale operation, TRWD found that the results indicated that constructed wetlands provided significant removal of nutrients and solids, as well as had the potential of providing long-term removal of these constituents. Based on the results of the pilot-scale wetlands, TRWD started the next phase of their water reuse project. This phase, known as the field-scale wetlands, is the first stage of the full-scale wetland system to be constructed for one of the District's reservoirs.

The purpose of this study was to evaluate the first two years of operation of the field-scale wetlands, primarily addressing nutrient removal efficiency. The work that TRWD is doing is the first of its kind in the nation, mainly because the treated wastewater coming out of the constructed wetlands is eventually going to be used to supplement an existing drinking water supply. The success of their work may lead to similar projects throughout the country.

1.1 Objectives

The goals of this study were to analyze the water quality data of TRWD's field-scale constructed wetlands and to evaluate the efficiency of the wetland system.

Specifically, the objectives of this study were to use the current field-scale water quality and vegetation data to:

1. Evaluate cell-to-cell and system-wide nutrient removal efficiency of TSS, TP and TN.
2. Identify relationships among the various water quality and vegetation parameters.
3. Compare the results of the field-scale wetlands to those of the pilot-scale wetlands to identify potential improvements that can be made in the field-scale wetland system.

The first objective of this study was to evaluate nutrient removal efficiency of each individual wetland cell, as well as the wetland system as a whole. For the purposes of this study, removal efficiency is basically the difference in the amount of nutrient concentration coming into and out of the wetland cell. Efficiency for the entire wetland system will consider the Trinity River as the initial concentration and the last wetland cell as the output concentration. For the purposes of this study, dilution effects such as rainfall, evapotranspiration and runoff were not considered in the removal efficiency of these nutrients.

The next objective of this study was to address any relationships that might be occurring among the vegetation and water quality parameters. The vegetation composition of each individual wetland cell may have a direct effect on the removal efficiency of TSS, TP and/or TN. The amount of vegetation present, as well as the variety that does or does not exist in each cell may play an important role in nutrient removal efficiency. Likewise, the dominance of one or two species in a particular wetland cell may impact the cell's removal efficiency.

The final objective of this study was to compare the nutrient removal efficiency results of the field-scale wetlands to those of the pilot-scale wetlands to identify areas that can be improved upon in the field-scale wetlands. While the obvious difference in the results will be due to the difference in size and operational time of each system, the primary difference will likely be due to the mechanics of the systems, along with the vegetation composition of each wetland cell/system. The pilot-scale operation yielded mass balance equations/results for TSS, TP and TN; however, these equations have yet to be solidified for the field-scale wetlands. As a result, comparisons of mass balance results will not be made in this study.

II. LITERATURE REVIEW

2.1 Water Supply/Demand Issues for Region C

As of 1998, Region C (Figure 2.1) contains over 24% of Texas' total population (Region C Water Plan 2001) and includes 12 of the 20 fastest-growing communities in the state (NWF 2005). Water use in Region C has increased significantly in response to this high rate of population growth and municipal demand.

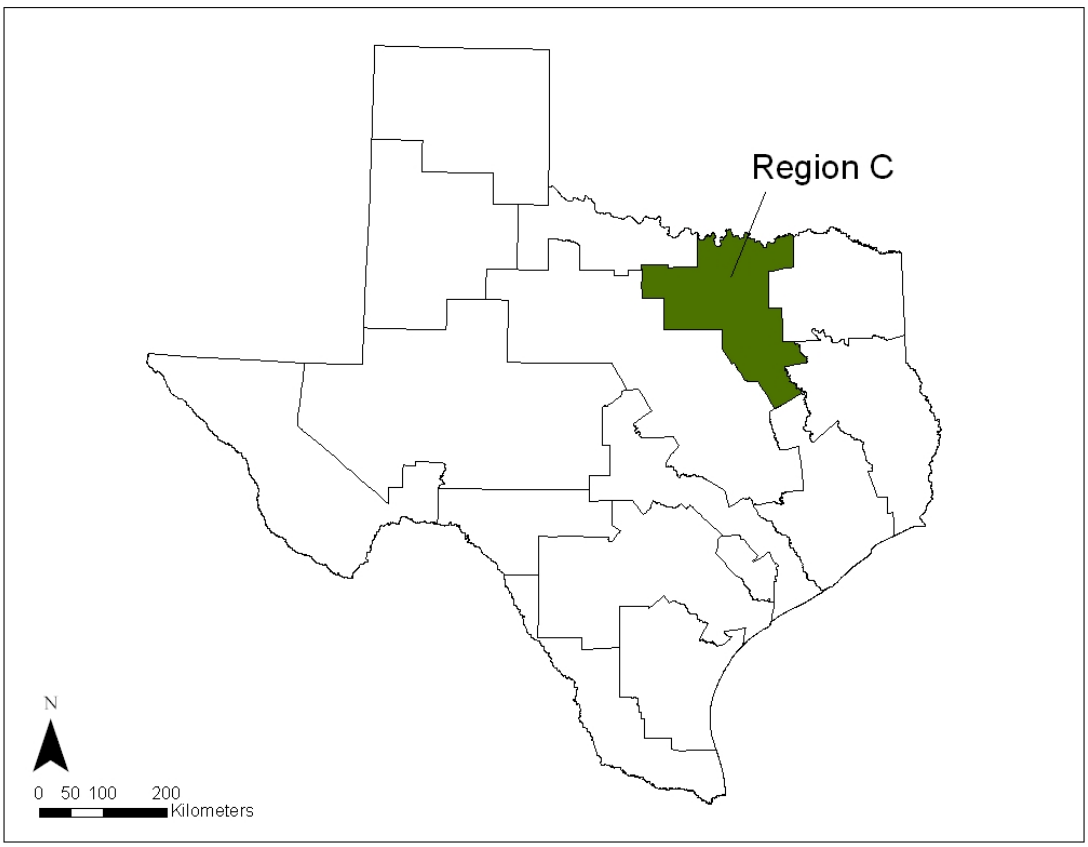

Figure 2.1. Texas regional water planning areas.

Currently, over 90% of the water supplied to Region C is from surface water (Region C Water Plan 2001). Groundwater, an important source of water for the area, is mainly allocated to the rural areas in the region, while municipal demands are primarily supplied with surface water from one of the area's 34 existing reservoirs. Reservoirs prove to be a reliable source of water for Region C because of their high water storage capacities, especially during high flows from the Trinity River and other rivers and streams located within the region. This is extremely beneficial to the region when the area is experiencing low flows and drought conditions.

Over half of the water supplied to the region's municipalities comes in the form of treated effluent from wastewater treatment plants (Region C Water Plan 2001). This allows water management strategies such as wastewater reclamation and water reuse, both of which are acceptable practices in Region C's long-term water plan, to potentially become an additional water supply for the region (Region C Water Plan 2001).

2.2 TRWD's Need for a Water Reuse Strategy

TRWD recognized the potential of using a water reuse strategy to supplement existing water supplies (i.e., reservoirs). This type of strategy would help TRWD provide a reliable source of water to its customers in the future. TRWD's customer base primarily consists of the cities of Fort Worth, Mansfield and Arlington, which are located in Tarrant County (one of the most heavily populated counties in Region C). Population projections (Table 2.1) and water demand projections (Table 2.2) for Tarrant County illustrate the need for additional water supplies, such as the one developed by TRWD.

Table 2.1. County population projections for Region C.

	Historical[1]	Projected Population Growth					
	1996	2000	2010	2020	2030	2040	2050
Tarrant County	1.31	1.42	1.59	1.8	1.92	2.11	2.21
Region C Total[2]	4.61	5.01	5.88	6.93	7.85	8.78	9.48

[1] Population values are in the millions.
[2] Sum of the 16 counties in Region C
Source: Region C Water Plan 2001.

Table 2.2. County water demand projections for Region C.

	Historical[1]	Projected Water Demand					
	1996	2000	2010	2020	2030	2040	2050
Tarrant County	35,945	46,775	52,248	57,817	60,559	65,093	68,249
Region C Total[2]	138,955	169,774	209,158	239,900	265,179	292,113	312,924

[1] Values are in hectare-meter per year.
[2] Sum of the 16 counties in Region C
Source: Region C Water Plan 2001.

Out of all of the long-range water supply options that TRWD evaluated, diverting water from the Trinity River was the most feasible. TRWD selected two of their existing drinking water reservoirs, Richland-Chambers and Cedar Creek, to receive the diverted water from the Trinity River (Figure 2.2). It is estimated that this diversion into the two reservoirs will yield an additional 14,246.72-ha-m per yr from these two reservoirs (APAI 2002).

As previously mentioned, there is a considerable amount of treated effluent discharged from the Dallas-Fort Worth Metroplex's wastewater treatment plants. The Trinity River receives a large amount of these treated wastewater discharges. In order to introduce the diverted river water into the reservoirs, a secondary wastewater treatment option is required. TRWD selected constructed wetlands as the secondary treatment method. Their ultimate goal for the constructed wetlands is to achieve water quality comparable to the water coming into the reservoirs from the natural tributaries.

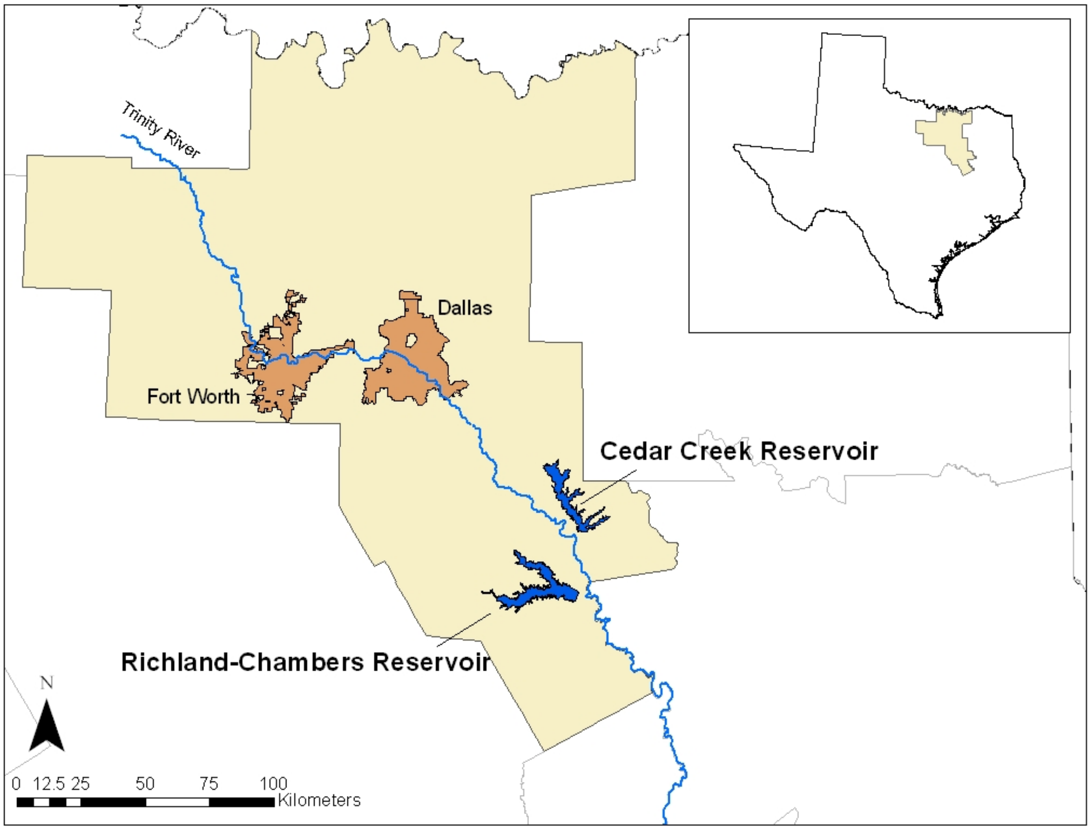

Figure 2.2. Richland-Chambers and Cedar Creek reservoir boundaries.

2.3 Constructed Wetlands

The use of wetlands to improve water quality is well-documented (Kadlec and Kadlec 1979, Johnston 1991, Kadlec 1995, Kadlec and Knight 1996, Mitsch and Gosselink 2000). Several wetland functions that are important to water quality improvement include, but are not limited to: (1) retain surface water, which helps to decrease floods and the heavy pollution loads associated with floods (Mitchell et al. 1995, Straškraba 1996); (2) serve as filters or buffer zones for pollution, thereby reducing metal and nutrient concentrations (Mitchell et al. 1995, Straškraba 1996, Anderson et al. 2003); and (3) serve as sinks for nutrients, which allows for nutrient retention through processes such as sediment deposition (Fennessy et al. 1994). Kadlec and Knight (1996) found wetlands (natural or constructed) to be effective in treating biochemical oxygen demand (BOD), suspended solids, nitrogen and phosphorus, and for reducing concentrations of metals, organics and pathogens. Day et al. (2004) reviewed past work and stated that wetlands efficiently remove nutrients through physical, chemical and biological processes. These processes include excess nutrient removal through settling and filtration (physical), precipitation and adsorption (chemical), and sediment accumulation, storage/uptake in vegetation and denitrification (biological) (Hemond and Benoit 1988, Day et al. 2004).

Current literature shows that constructed wetlands have been designed specifically to treat water pollution from contaminated surface and wastewaters (Reed et al. 1995, Kadlec and Knight 1996, Nairn and Mitsch 2000, Andersson et al. 2005). Mitsch and Gosselink (2000) mention a number of studies pertaining to wastewater wetlands and point out that constructed wetlands that treat wastewater have been most effective in controlling organic matter (BOD), suspended solids and nutrients. Additionally, constructed wetlands are an attractive option for wastewater treatment because they are cost efficient and they require low maintenance and operation (Dunbabin and Bowmer 1992, Lin et al. 2002, Nokes et al. 2003). While the costs associated with constructing a wetland are not inexpensive, they are usually less than the alternative treatment processes (Reed et al. 1995, Mitsch and Gosselink 2000). In fact, TRWD estimates that the costs of constructing their treatment wetlands is about half of what it would cost to build a new reservoir (Mr. Darrel Andrews, TRWD, *personal communication*).

The disposal of wastewater into wetlands is not a new practice. In fact, Best (1987) points out that waste products have been discharged into wetlands for centuries. Over the past 20-30 yrs, the use of wetlands (both natural and constructed) as biological treatment systems for effluent purification has grown in popularity (Dunbabin and

Bowmer 1992, Lin et al. 2002). Nairn and Mitsch (2000) mention a number of studies about constructed wetlands used to treat effluent from municipal wastewater, animal wastes, septage, pulp mill wastes and mine drainage. Little work has been done on pretreated effluent from river water. Jing et al. (2001) found that constructed wetlands effectively removed nutrients from a highly polluted river in Taiwan, but the river in their study was a low-flow river and the wastewater effluent was untreated.

TRWD's water reuse project using constructed wetlands as a means of secondary treatment to polish pretreated wastewater from the Trinity River (a high-flow river) is unique. Other water reuse projects that have relied on wetlands to polish treated wastewater have recycled the water in different ways. For instance, polished wastewater has been used for crop irrigation and for watering parks and gardens, playing fields and golf courses (Greenway 2005). Recycled wastewater has also been discharged into groundwater and surface water (Mitsch and Gosselink (2000). The primary difference between past reuse projects and the one that TRWD is performing is that the recycled water will put into an existing drinking water supply, and thus will be used for human consumption.

2.4 TRWD's Constructed Wetlands: Pilot-Scale

In order to prove that using constructed wetlands to secondarily treat water from the Trinity River was a viable option, TRWD initiated the testing phase of the project, otherwise known as the pilot-scale wetland system. This system was located in the Trinity River floodplain near the Richland-Chambers Reservoir.

In 1991, a consulting firm, Alan Plummer Associates, Inc. (APAI), designed the pilot-scale wetlands for TRWD. Construction of the pilot-scale system, which included two settling ponds and three parallel wetland treatment trains (each consisting of three individual wetland cells) began in July of 1992 and was completed in October of 1992. The nine wetland cells were similar in area (0.1-ha) with an average depth of 0.5-m, while the two settling ponds varied in size. One of the sedimentation ponds (SB 1) had a surface area of about 0.03-ha and the other (SB 2) was approximately 0.08-ha, while both had an average depth of 2-m (Figure 2.3).

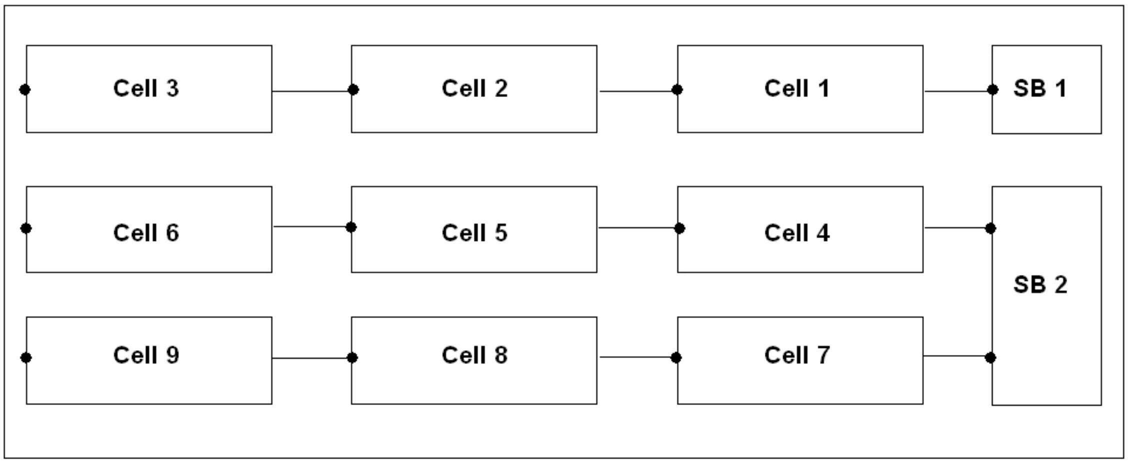

Figure 2.3. Schematic presentation of the pilot-scale wetland system. Train 1 consisted of wetland cells 1-3; train 2 contained of wetland cells 4-6; and train 3 consisted of cells 7-9. Sedimentation pond 1 (SB 1) preceded train 1, while sedimentation basin 2 (SB 2) preceded trains 2 and 3. "•" represents weir locations at each wetland cell and settling pond. Diagram adapted from APAI (2002).

During the eight-yr period that TRWD operated the pilot-scale wetlands, over 400-wks of operational data were collected. According to TRWD and APAI, data collection was occasionally interrupted by flooding events, droughts, mechanical breakdowns and structure repairs from wildlife activity (APAI 2002). Some of the specific goals for the pilot-scale project included: (1) development of data on removal efficiencies of wetland cells for nutrients, heavy metals, total suspended solids and selected toxic organics; and (2) evaluation of the suitability of various aquatic macrophyte plants and communities.

2.4.1 Removal Efficiency. TRWD's sampling program involved routine monitoring of physical parameters, such as daily rainfall, water temperature, pH, dissolved oxygen (DO), and water depth, with weekly analysis of various parameters. Mass balance calculations for the three main constituents of concern, total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP), were performed each week. The flow balance and mass balance models used for analysis during the pilot-scale testing, along with a brief description of each model, is in Appendix A.

The pilot-scale wetland system provided consistently effective removal of solids and nutrients. The concentrations of TSS, TP and TN were of higher quality than the concentration levels from the tributaries that naturally feed into the Richland-Chambers Reservoir (TRWD 2002). At the completion of the pilot-scale testing phase, nutrient removal was greater than 95, 80 and 65% for TSS, TN and TP, respectively (APAI 2002).

A number of special studies were also performed during the pilot-scale phase. Sediment and vegetation sampling were conducted annually to test for the potential bioaccumulation of toxic organics and metals (APAI 2002). Results indicated no bioaccumulation of pesticides or other toxic organics in the collected sediments and/or vegetation biomass (APAI 2002). Additionally, heavy metal accumulation in both sediments and vegetation did not represent any biohazard based on established criteria (APAI 2002).

2.4.2 Vegetation. Since the pilot-scale wetlands were located in a floodplain (a habitat prone to experience occasional flooding), the area was already conducive to wetland plant species. Therefore, indigenous plants were used throughout the system. Vegetation species consisted of emergent macrophytes, floating species and submerged species. Out of the three wetland trains, only the cells located in trains 1 and 2 had selective vegetation planted in them, leaving the wetland cells in train 3 to grow naturally. Vegetation composition and density varied among the six cells that were selectively planted.

In order to determine species presence and abundance, four 1-m^2 quadrats for each wetland cell were staked out for vegetation monitoring. Photos were taken of each quadrat during each sampling period, and the vegetative cover within the quadrat was analyzed (Ms. Loretta Mokry, APAI, *personal communication*). This surveying routine was performed throughout the entirety of the pilot-scale wetlands system.

The top five dominant species for each wetland cell, as well as for the entire pilot-scale wetland system are listed in order of dominance in Table 2.3. The species showing the best adaptability and survival under various operating conditions are grassy arrowhead (*Sagittaria graminea* Michx.), softstem bulrush (*Scirpus validus* Vahl), cattail (*Typha latifolia* L.), squarestem spikerush (*Eleocharis quadrangulata* (Michx.) R.and S.), coontail (*Ceratophyllum demersum* L.) and duckweed (*Lemna spp.*) (APAI 2002). A complete listing of all of the vegetation species found in the pilot-scale wetland cells is in Appendix B, Table B-1.

Table 2.3. The top five dominant species for each pilot-scale wetland cell, along with the pilot-scale wetland system.

	Common Name	**Scientific Name**	**Author**
Cell 1	Duckweed	*Lemna spp.*	
	Softstem Bulrush	*Scirpus validus*	Vahl
	Water Primrose	*Ludwigia peploides*	HBK.
	Arrowhead	*Sagittaria graminea*	Michx.
	Toothcup	*Ammania coccinea*	Rottb.
Cell 2	Coontail	*Ceratophylum demersum*	L.
	Squarestem Spikerush	*Eleocharis quadrangulata*	(Michx.) R.& S.
	Cattail	*Typha latifolia*	L.
	Crowfoot Sedge	*Carex crus-corvi*	Shuttlw. ex Kuntze
	Duckweed	*Lemna spp.*	
Cell 3	Arrowhead	*Sagittaria graminea*	Michx.
	Coontail	*Ceratophylum demersum*	L.
	Duckweed	*Lemna spp.*	
	Smartweed	*Polygonum hydropiperoides*	Michx.
	Mosquito Fern	*Azolla caroliniana*	Willd.

Table 2.3. Continued.

	Common Name	Scientific Name	Author
Cell 4			
	Duckweed	*Lemna spp.*	
	Arrowhead	*Polygonum hydropiperoides*	Michx.
	Mosquito Fern	*Azolla caroliniana*	Willd.
	Jungle Rice	*Echinochloa colonum*	(L.) Link
	Colorado River-hemp	*Sesbania herbacea* (formerly *macrocarpa)*	Muhl.
Cell 5	Coontail	*Ceratophylum demersum*	L.
	Duckweed	*Lemna spp.*	
	Arrowhead	*Polygonum hydropiperoides*	Michx.
	Mosquito Fern	*Azolla caroliniana*	Willd.
	Water Primrose	*Ludwigia peploides*	HBK.
Cell 6	Squarestem Spikerush	*Eleocharis quadrangulata*	(Michx.) R. & S.
	Coontail	*Ceratophylum demersum*	L.
	Water Primrose	*Ludwigia peploides*	HBK.
	Crowfoot Sedge	*Carex crus-corvi*	Shuttlw. ex Kuntze
	Toothcup	*Ammania coccinea*	Rottb.
Cell 7	Cattail	*Typha latifolia*	L.
	Duckweed	*Lemna spp.*	
	Mosquito Fern	*Azolla caroliniana*	Willd.
	Arrowhead	*Sagittaria graminea*	Michx.
	Frog Fruit	*Lippia lanceolata*	Michx.
Cell 8	Duckweed	*Lemna spp.*	
	Softstem Bulrush	*Scirpus validus*	Vahl
	Coontail	*Ceratophylum demersum*	L.
	Water Primrose	*Ludwigia peploides*	HBK.
	Smartweed	*Polygonum hydropiperoides*	Michx.
*Cell 9**	Open Water		
	Colorado River-hemp	*Sesbania herbacea* (formerly *macrocarpa)*	Muhl.
	Water Primrose	*Ludwigia peploides*	HBK.
	Cattail	*Typha latifolia*	L.
	Toothcup	*Ammania coccinea*	Rottb.

Table 2.3. Continued.

	Common Name	Scientific Name	Author
System	Duckweed	*Lemna spp.*	
	Coontail	*Ceratophylum demersum*	L.
	Arrowhead	*Sagittaria graminea*	Michx.
	Water Primrose	*Ludwigia peploides*	HBK.
	Mosquito Fern	*Azolla caroliniana*	Willd.

*The majority of this cell consisted of open water.
Source: APAI 1999.

Upon the completion of the pilot-scale wetland system study, the vegetation data collected, along with information obtained on nutrient and other contaminant removal, indicates that the establishment of a mixture of selected species will enhance the overall treatment performance for removal of nutrients (APAI 2002). Additionally, an array of selected vegetation species will assist in the survival of plants and the reestablishment of vegetative cover following flood events, along with sustaining vegetative cover despite impacts from wildlife (APAI 2002). A list of recommended plant species from the pilot-scale testing is in Appendix B, Table B-2.

With the completion of the pilot-scale testing, TRWD began the first phase of their full-scale wetlands. This phase, known as the field-scale wetlands, is the first to be constructed for the Richland-Chambers Reservoir.

III. MATERIALS AND METHODS

3.1 Site Description

The field-scale wetlands, owned and operated by TRWD, are located approximately 40-km southeast of Corsicana, TX. The field-scale wetlands fall entirely in Navarro County; however, when the entire full-scale wetland system is completed, some of the wetlands will be in Freestone County as well. The field-scale site is located within the Post Oak Savannah and Blackland Prairie ecotones, and is included in the Trinity River flood plain (TPWD 2006). The area receives an average annual rainfall of approximately 102-cm, and is prone to periodic and prolonged flooding (TPWD 2006). Bottomland soils (primarily Trinity and Kaufman clays) mostly comprise the area and support both bottomland and wetland wildlife and vegetation communities (TPWD 2006).

Construction of the field-scale wetlands began in the summer of 2000 and was completed in December of 2002. The field-scale wetlands phase involved the construction of a river intake and pump station located at the Trinity River, a raw water pipeline (107-cm diameter and 1737-m long), a sedimentation basin (3-ha) and four wetland cells (ranging from 11 to 30-ha). Together, the four wetland cells comprise a total area of 98-ha and are able to support a flow of 56,781-m^3/d (Figure 3.1).

The field-scale wetland cells are shallow basin surface-flow wetlands, operating at an average depth of 0.32-m. Average depths for each wetland cell are listed in Table 3.1, along with other site characteristics. The first and second wetland cells were designed to include deep zones (areas where the water was deeper than the rest of the cell). These zones were generally 1.5 – 1.8-m deep. TRWD included these deep zones to promote equal dispersion across the wetland cell, encourage natural processes (i.e., denitrification) and support waterfowl activity (Mr. Darrel Andrews, TRWD, *personal communication*).

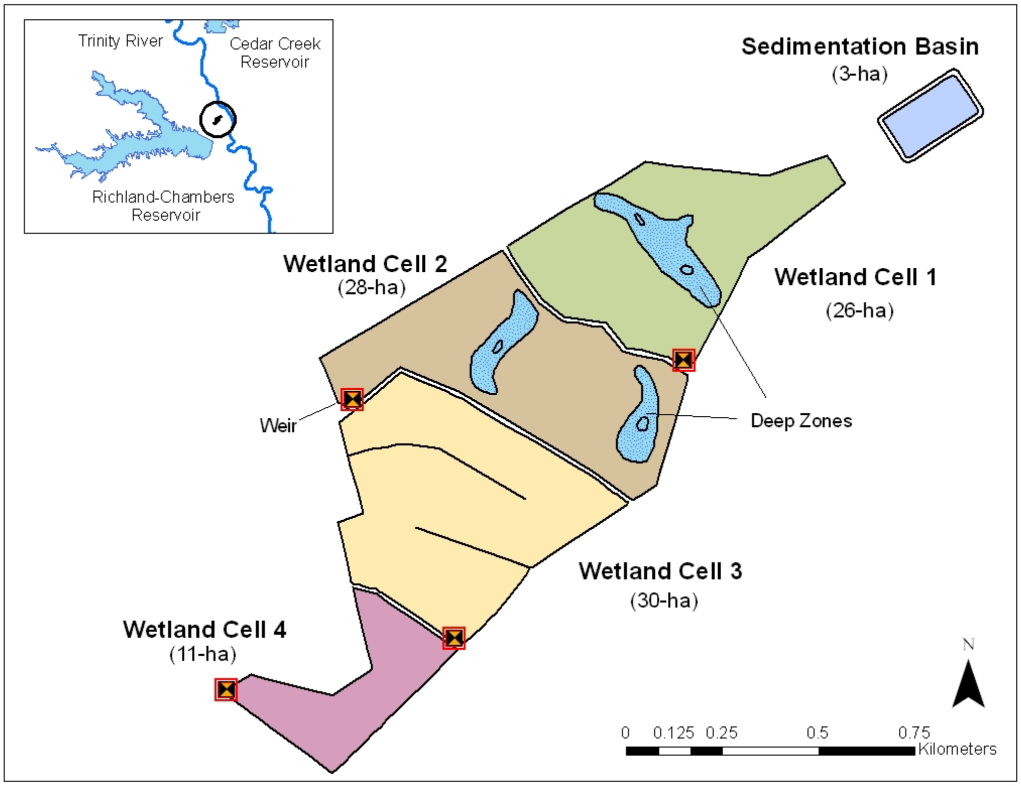

Figure 3.1. The field-scale operation consisted of four wetland cells and one sedimentation basin.

Table 3.1. Characteristics of each wetland cell in the field-scale system.

Wetland Cell	Area (ha)	Avg. Depth (m)	Avg. Volume* (m^3)	Detention Time**(d)
WC1	26	0.35	90,412	2.49 - 2.7
WC2	28	0.37	100,492	2.17 - 2.61
WC3	30	0.31	94,825	1.61 - 1.94
WC4	11	0.23	25,516	0.58 - 0.78

*Average volume calculations are from two separate measurements (April and October 2004).
**Detention times are for 45,424.94 and 56,781.18-m^3d^{-1} flow rates.

The logistics of the field-scale system are as follows: water is pumped from the Trinity River at the intake station and passed through the raw water pipeline into the sedimentation basin. The water is retained in the settling pond for approximately seven to eight hours. Water then moves into wetland cell 1 and continues to move throughout the system until it passes through wetland cell 4. This entire process takes approximately seven days. The treated water is then released into Alligator Creek, a tributary that feeds into the Trinity River. Treated river water will not be pumped into the Richland-Chambers Reservoir until the entire full-scale wetland system is complete. This will allow TRWD to confirm that each phase of the full-scale wetlands is achieving the desired nutrient removal before the polished water is added to the reservoir.

The field-scale system provides TRWD with information on the reliability of using wetlands to treat river water under a more realistic operational setting. TRWD operates and monitors the field-scale wetlands in a similar manner to that of the pilot-scale wetlands. This helps to verify the results of the pilot-scale project and to ensure that no unforeseen problems arise due to the increased size of the operating system (TRWD 2002).

Texas Parks and Wildlife (TPWD) partnered with TRWD in the implementation of the field-scale wetlands and will continue to work together throughout the establishment of the full-scale system. The field-scale wetlands, and eventually the full-scale system, are located on the North Unit of TPWD's Richland Creek Wildlife Management Area (WMA). The Richland Creek WMA is an ideal location for constructed wetlands because of the bottomland hardwood habitats that represent the area, both currently and historically. In fact, the Richland Creek WMA was created in response to the habitat losses associated with the construction of the Richland-Chambers Reservoir (TPWD 2006).

The constructed wetland system addresses two major goals of the Richland Creek WMA: (1) enhance habitat for a variety of wildlife species, including indigenous and migratory waterfowl; and (2) provide additional public outdoor recreational opportunities, such as hunting and bird watching (TRWD 2002). The partnership among the two agencies intends to make the constructed wetlands an integrated water supply and wildlife habitat system (TRWD 2002).

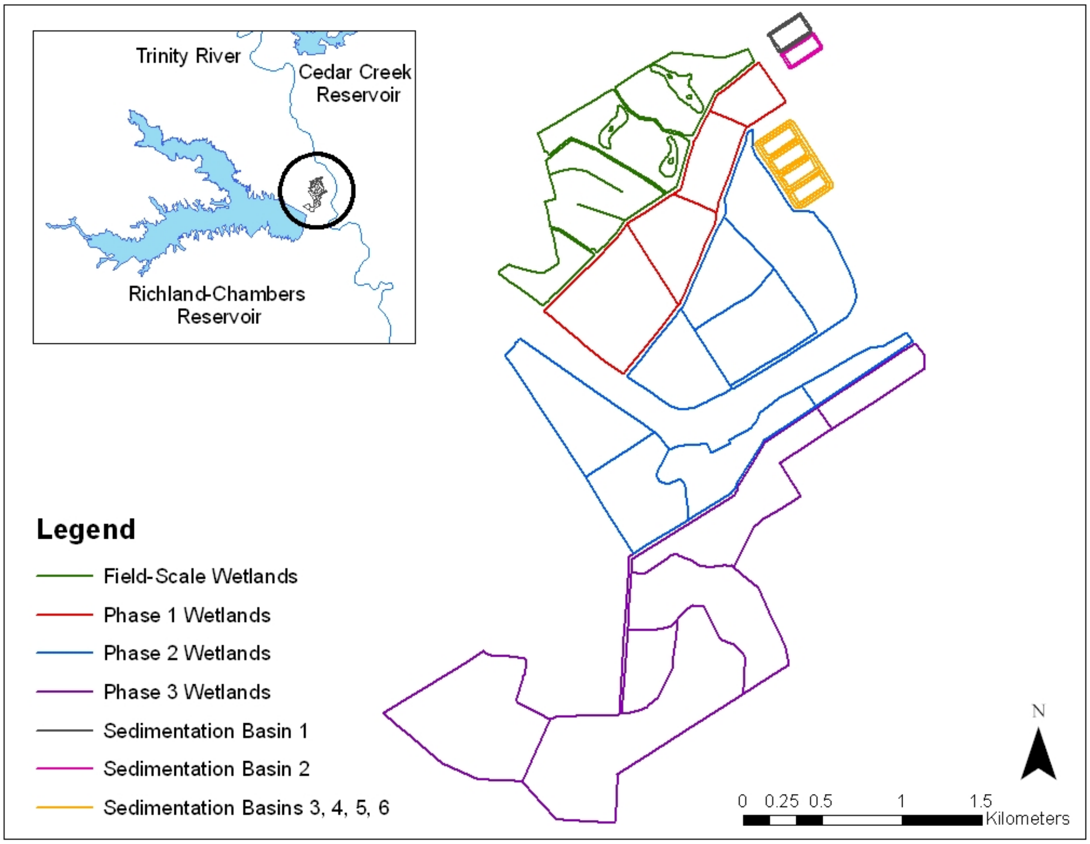

Figure 3.2. Full-scale wetland system for the Richland-Chambers Reservoir. The combined acreage for the entire wetland system is approximately 809-ha.

The next phase of the full-scale wetland system is set to begin in 2006, with the addition of 81-ha of wetlands and another sedimentation pond. This phase will also include the construction of another pump station that will pump water from Alligator Creek into the Richland-Chambers Reservoir. Two additional phases of wetlands and a series of four connected sedimentation basins will follow, thus completing the full-scale wetland system for the Richland-Chambers Reservoir. When the full-scale wetland system is completed (Figure 3.2), the total area of constructed wetlands will be over 809-ha and the total treatment capability will be 378,541-m^3/d (TRWD 2002).

Upon completion of the full-scale wetlands for the Richland-Chambers Reservoir, TRWD will begin the next phase of their water reuse project with the construction of another wetland system for the Cedar Creek Reservoir. The Cedar Creek wetlands will be comparable to the Richland-Chambers wetland system, comprised of approximately 809-ha of wetlands. Together, the two systems will contribute around 1619-ha of managed wetlands to the Trinity River floodplain for water supply.

3.2 Data Collection

TRWD has completed over two years of operation of the field-scale constructed wetland system. While the operation is still in the initial stages, TRWD has collected, and continues to collect, a substantial amount of information on water quality and vegetation parameters. As of May 2005, TRWD has obtained 69-wks of field data (consisting of 123 sampling days) and 66-wks of lab data (66 individual sampling days) for various water quality parameters. Vegetation samplings have not been as numerous as what has been done for the water quality variables, but there is still a considerable amount of plant species information that has been gathered. For this project's analysis of the field-scale wetlands, only the data that was collected for the first two operational years, from June 2003 to May 2005, will be considered.

For the first year of operation, data collection began in June of 2003 and was completed in May of 2004. In late May/early June of 2004, pumping was temporarily discontinued to draw down the water in the wetland cells to allow TRWD to perform some scheduled maintenance to the cells. Cell maintenance included the alteration of existing dispersion berms (for erosion control), the creation of new deep zones (in wetland cells 1 and 3) and dispersion berms (for flow dispersion), and the removal of existing dispersion berms that were ineffective in channelizing the flow (Mr. Darrel Andrews, TRWD, *personal communication*).

Pumping resumed in September of 2004 and continued throughout the wetland system until late March 2005. On 28 March 2005, TRWD started bypassing wetland cells 1 and 2 to allow the cells to drain for the planting of additional vegetation species. At this time, water continued to be pumped from the river and passed through the sedimentation basin, but the water was diverted from wetland cells 1 and 2. Water was allowed to flow through wetland cell 3 and the remainder of the wetland system. In early May of 2005, TRWD began pumping water back through wetland cell 1; however, water was still diverted from passing through wetland cell 2. This cell, along with wetland cell 3, was drained to allow for the control of black willows (*Salix nigra* Marsh.). Pumping resumed for wetland cell 2 in early July of 2005, and in late August of 2005 for wetland cell 3.

TRWD kindly supplied all of the water quality data that has been collected for both the pilot-scale and field-scale wetlands, along with all of the reports from APAI for the pilot-scale wetlands. The area's historical vegetation data were supplied by TPWD, and APAI provided the vegetation data for the field-scale data, along with the quarterly vegetation surveys. Currently, TRWD monitors water, vegetation and soil parameters for the field-scale wetlands.

3.2.1 Water Quality. Water samples were collected on a weekly basis at seven sites in the wetland system (pump station, sedimentation basin, each wetland cell, and at Alligator Creek). The sample locations are referred to as PS, SB, WC1, WC2, WC3, WC4 and AC. The parameters that were recorded in the field, using either Hydrolabs or YSI units, included: water temperature, pH, DO, conductivity, gauge, weir height, weir flow and flow. Also recorded at this time were date, site, time of day, air temperature and rainfall. The parameters measured in the field were conducted on average one to two times per week.

Parameters analyzed in a laboratory located at TRWD's Richland-Chambers location included: total suspended solids (TSS), total volatile suspended solids (TVSS), total phosphorus (TP), organic phosphorus (OP), nitrate and nitrite (NOX), ammonia (NH3), total Kjeldahl nitrogen (TKN), alkalinity, hardness, chlorophyll and turbidity. The methods used for the analysis were as follows: TSS and TVSS were analyzed according to the methodology presented in Standard Methods (APHA 1989); TP was analyzed using the persulfate digestion method outlined in Standard Methods (APHA 1989); OP was analyzed by the automated ascorbic acid method (APHA 1989); NOX was analyzed by the Hach Method's (Hach Methods 1995) cadmium reduction method; NH_3 was analyzed by the Nesslerization Method presented in Standard Methods (APHA 1989); TKN was analyzed using the macro-Kjeldahl method (APHA 1989); alkalinity, hardness and chloride were analyzed by the titration methods described in Hach Methods (1995). Total nitrogen (TN), which is the sum of NOX and TKN added together, was also included with the chemical parameters results. Parameter analysis in the lab occurred on a weekly basis.

3.2.2 Vegetation. APAI, together with TRWD, conducted near quarterly vegetation surveys. Since the establishment of the field-scale wetland system, vegetative cover surveys have been conducted on 27 August 2003, 21 November 2003, 5 March 2004, 18 May 2004, 22 March 2005 and 20 June 2005. The surveys were generally performed at the end of each season, with the exception of the March 2005 and June 2005 surveys. The timing of these two vegetation surveys actually occurred at the beginning of a season, but for consistency purposes in this research, the March 2005 and June 2005 surveys were reported as end-of-the-season surveys. Vegetation surveys were not performed during the summer months of 2004 due to a scheduled drawdown and operation maintenance.

During the first vegetation survey in August 2003, two 76-m long transects were located and staked in each wetland cell for permanent identification for future vegetation monitoring. In addition to the two 76-m long transects, WC4 had a 20-m long transect line across the shallow plant shelf located in the west end of the cell. This shorter transect is necessary because the vegetative community in this portion of WC4 represents a different habitat than the rest of the marsh area within the cell (APAI 2003). Location of the transect lines are illustrated in Figure 3.3.

The vegetation surveys included species identification and abundance approximation at 2-m intervals along each of the transect lines. Visual approximation was used to assess the presence and identification of vegetation species within a 0.9-m radius around each 2-m interval point. While this approximation within the 0.9-m radius was used to determine species presence and abundance, the main focus was on the vegetation that immediately intersected the 2-m interval point (Ms. Loretta Mokry, APAI, *personal communication*). In all of the surveys conducted thus far, more than one species was identified at each intersection point.

The order of dominance of all the plant species at each 2-m intersection was visually approximated. Dominance ranking was done on a scale of one to five. Five represents the most abundant (dominant) species and one represents the least abundant species. Where vegetation was sparse, open water was designated as the dominant cover type. When less than five species were identified at the intersection point, the ranking of five was still assigned to the most dominant species with numbers assigned in receding order for the number of species identified (APAI 2003). The dominance ranks for each species were combined to assess the total dominance values for each individual wetland cell, as well as for all of the wetland cells together.

In addition to the vegetation transects, APAI conducted photo monitoring of the wetland system's vegetation. Photographs of the vegetative cover were taken at designated photo stations, including each of the transect locations and various other sites (Figure 3.3). The photos were used for qualitative purposes in that the photos were just landscape shots taken at the selected stations (Ms. Loretta Mokry, APAI, *personal communication*).

3.2.3 Soil. TRWD conducted soil sampling on an annual basis and sent all soil samples to a private lab in Denton, TX for analysis. The field-scale sediment sampling was similar to what was done for the pilot-scale wetland system.

Throughout the pilot-scale operational period, thorough analyses of the sediment were performed to primarily assess bioaccumulation of toxic organics and metals. Results for both nitrogen and phosphorus indicated that no significant accumulation was occurring. Likewise, TRWD found no consistent trend of increasing metal accumulation. In fact, levels of metal concentration reported over the pilot-scale operation did not appear to be significantly different from the levels reported from the background sampling conducted at the field-scale project site (APAI 2002).

Results such as these strengthened TRWD's decision to use the same routine monitoring as what was conducted during the pilot-scale study. Due to the limited quantity of available data, soil analyses were not addressed in this study.

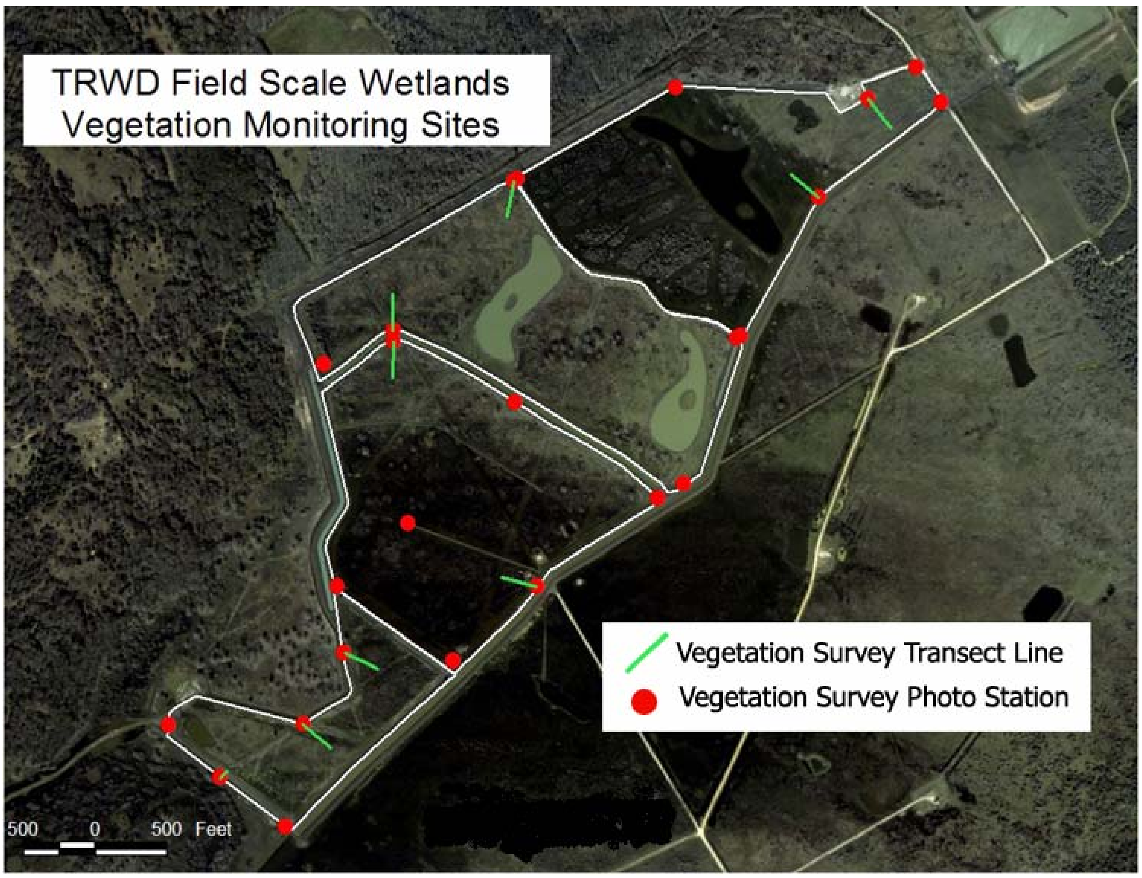

Figure 3.3. Vegetation monitoring sites for the field-scale wetlands. The green lines represent the vegetation survey transect lines and the red points denote the vegetation survey photo stations. Source: APAI 2002.

3.3 Statistical Analysis

MS Excel 2002 was used to run all of the statistical analyses. The basic statistics that were determined include:

- Average concentrations for each water quality parameter on a monthly, seasonal and yearly basis.
- Correlation coefficients among the parameters to assess any relationships that may be occurring.
- Normalization of the vegetation data according to the area of each wetland cell.
- Percent reductions for select parameters to determine removal efficiency.

3.3.1 Average Concentrations. Monthly statistics were derived for each month in which the field-scale wetland system was operating during the time frame of this study (June 2003 to May 2005). The following months were not included: June 2004, July 2004, August 2004 and December 2004. The seasonal analyses were comprised of the following seasons: Summer (June – August), Fall (September – November), Winter (December – February) and Spring (March – May). Due to maintenance, the summer of 2004 had no data, and thus this season was not included in the seasonal analysis. Yearly statistics consisted of results for the first two years of operation. The first year of operation was from June 2003 to May 2004 and second year was from September 2004 to May 2005.

Means and standard deviations were calculated for each water quality parameter (17 parameters total). In keeping with the pilot-scale study, only three parameters (TSS, TP and TN) were used in further mean concentration analyses.

3.3.2 Correlations. Correlation matrices were derived for all of the water quality parameters on a yearly basis. Only those parameters having a significant correlation relationship were utilized for analysis purposes. Ranges of significant correlation values were arbitrarily selected for this project. These ranges included: $1 \geq x \geq 0.4$ and $-1 \leq x \leq -0.4$.

3.3.3 Vegetative Cover. The field-scale wetland vegetation data were normalized according to each wetland cell's area. To normalize the data, the sums of the dominance ranks for each vegetation species were divided by the wetland cell's area. The normalized data were then used to compute cumulative abundance, as well as the percent cover for each vegetation species. Cumulative abundance per species was calculated by dividing the ranking sum of each individual species by the total ranking for all of the vegetation species together. This amount was then multiplied by 100 to obtain the percent cover. Since vegetation surveys were conducted on a quarterly basis, only seasonal analysis was allowed for the vegetation data.

3.3.4 Percent Reductions. Assuming the wetland system is running as it is intended to run (i.e., no blocked weirs, no bioturbation, etc.), nutrient concentrations should decrease as they move along the system, while the percent reductions should increase. Percent reductions were developed for TSS, TP and TN to illustrate removal efficiency. The sums of the parameters were analyzed on a seasonal basis. Percent reductions were derived from the monthly data using the input and output concentrations (Equation 1).

$$((\text{Input } [x] - \text{Output } [x]) / \text{Input } [x]) * 100 \qquad (1)$$

The removal efficiency of TSS, TP and TN for each site was calculated. For instance, the first calculation considered the pump station as the input concentration and the sedimentation basin as the output concentration. This yielded the SB's removal efficiency of the three parameters. The next calculation had the sedimentation basin and WC1 as the input and output concentrations, respectively, and thus determined the removal efficiency of WC1. This process continued until the last wetland cell in the system was the output concentration. In addition to the treated wastewater from the wetlands, Alligator Creek also receives agricultural and storm water runoff. As a result of these additional inputs, Alligator Creek was not included in the percent reduction analysis.

Statistical analyses were conducted to determine significant differences (Student's *t*) between paired inflow and outflow concentrations of TSS, TP and TN between the phases of the wetland system. This procedure determined whether the nutrient removal of each site was significant.

3.4 N:P Ratios

N:P ratios were calculated for each site within the field-scale wetland system. TP and TN values for the two-year study period were converted from mgL^{-1} to $gmol^{-1}$. TP values were multiplied by 31 and TN values were multiplied by 14 to convert to moles. The averages of the molar units for TP and TN were used in the ratio analysis.

3.5 Moist-Soil Management

The draw down of water during the summer months of 2004 also allowed TRWD and TPWD to initiate moist-soil management to the wetland cells. Moist-soil management consists of applying or removing water at designated times to encourage germination, growth and seed production of plants (Gray and Bolen 1987, Haukos and Smith 1993). TPWD primarily wanted to promote the growth of annual plant species to provide a more preferred diet for migrating waterfowl.

A superficial analysis using [TSS], [TP] and [TN] and percent reduction data will be used to evaluate and identify differences before and after moist-soil management. Specifically, the original start-up data (June 2003) will be compared with the start-up data after the wetlands were managed for moist-soil plants (September and October 2004). The cells were reflooded in late September 2004; therefore, the month of October was included in this analysis. Vegetation data will not be used in the analysis because a vegetation survey was not conducted in the Fall 2004 season, and therefore, an accurate comparison cannot be made between the two start-up periods.

3.6 Pilot-Scale versus Field-Scale Wetland Systems

Overall removal efficiencies of the three parameters in the pilot-scale and field-scale systems were compared to determine which system had better removal. Similarly, individual wetland cells from each system were compared. In particular, a comparison was made between the cell/train that had the best removal efficiency in the pilot-scale wetland system with the cell that had the highest removal efficiency in the field-scale wetlands.

IV. RESULTS

4.1 Average Concentrations

Means and standard deviations for each water quality parameter were calculated on a monthly, seasonal and yearly basis. The yearly means and standard deviations for the water quality parameters represent all of the sampling events for the entire wetland system (Table 4.1). Yearly means and standard deviations for all of the parameters at each individual site are reported in Appendix C, Table C-1. Monthly and seasonal statistics for each water quality parameter for the entire wetland system are also reported in Appendix C, Tables C-2 through C-3.

Table 4.1. Means and standard deviations for the water quality parameters on a yearly basis (from June 2003 to May 2005). All sites (PS – AC) are included in the analysis.

Parameter	Mean	Std. Dev.	Sample Size (n)*
TSS (mgL^{-1})	60.57	107.29	442
TVSS (mgL^{-1})	7.66	9.23	433
TP (mgL^{-1})	0.59	0.3	450
OP (mgL^{-1})	0.55	0.32	450
NOX (mgL^{-1})	1.14	1.71	443
NH3 (mgL^{-1})	0.12	0.19	443
TKN (mgL^{-1})	0.67	0.36	443
TN (mgL^{-1})**	1.79	1.73	443
ALK (mgL^{-1})	122.68	33.08	182
HARD (mgL^{-1})	166.13	22.16	187
CHLOR (mgL^{-1})	50.76	20.47	430
TURB (ntu)	64.81	116.28	401
TEMP (° C)	21.11	7.59	761
pH (pH/units)	8.08	0.68	760
DO (mgL^{-1})	7.87	3.31	751
COND (μScm^{-1})***	583.55	122.00	759
FLOW (m^3d^{-1})	47173.74	13608.14	610

* Sampling size includes all of the sampling events taken at each site.
**Total Nitrogen is the sum of nitrite-nitrate (NOX) and total Kjeldahl nitrogen (TKN).
***Conductivity is measured in microsiemens per centimeter.

Average monthly, seasonal and yearly concentrations for the three main constituents of concern (TSS, TP and TN) display temporal variations in mean values for the entire wetland system. Likewise, average TSS, TP and TN concentrations vary spatially within the field-scale system. Temporal analyses include the field-scale wetland system as a whole, whereas the spatial analyses reflect each individual site within the wetland system.

4.1.1 Temporal Variability – Monthly Basis. Monthly averages for TSS were generally within the same range (40 to 85-mgL^{-1}); however, there were two months that fell outside of this range considerably (Figure 4.1). The value recorded for the month of September 2004 was much lower than the range, while the value for March 2005 was considerably higher. A comparison among the monthly [TSS] in the wetland system and the Trinity River resulted in a slope of 0.16 and an r^2 of 0.89 (Figure 4.2).

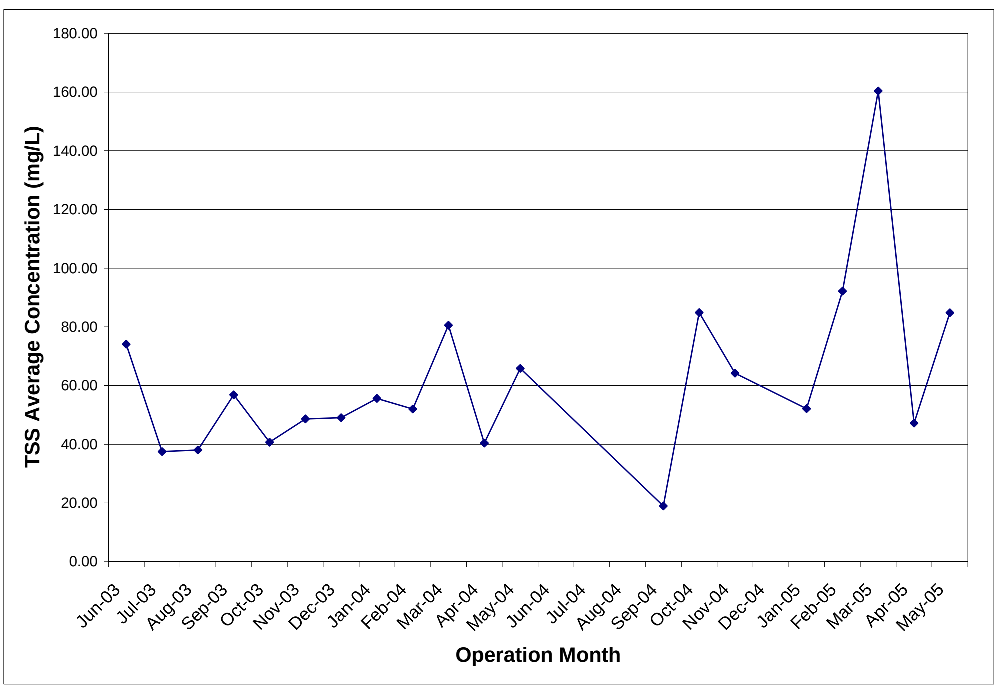

Figure 4.1. Monthly average concentrations for TSS across the wetland system. Data were not collected during the months of June 2004 through August 2004 and again in December 2004.

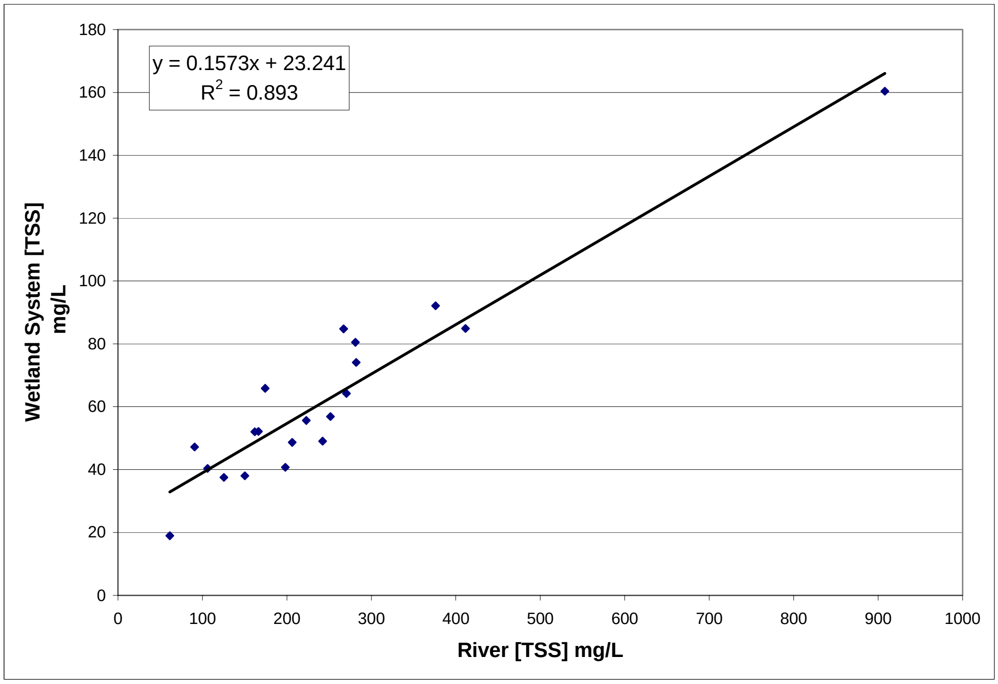

Figure 4.2. Comparison between monthly Trinity River [TSS] and wetland system [TSS].

Monthly averages for TP mostly fell within the 0.4 to 0.9-mgL^{-1} range. Two months (January and February 2005) were below the range (Figure 4.3). Monthly [TP] in the wetland system and the Trinity River were compared and resulted in a slope of 0.57 and an r^2 of 0.53 (Figure 4.4).

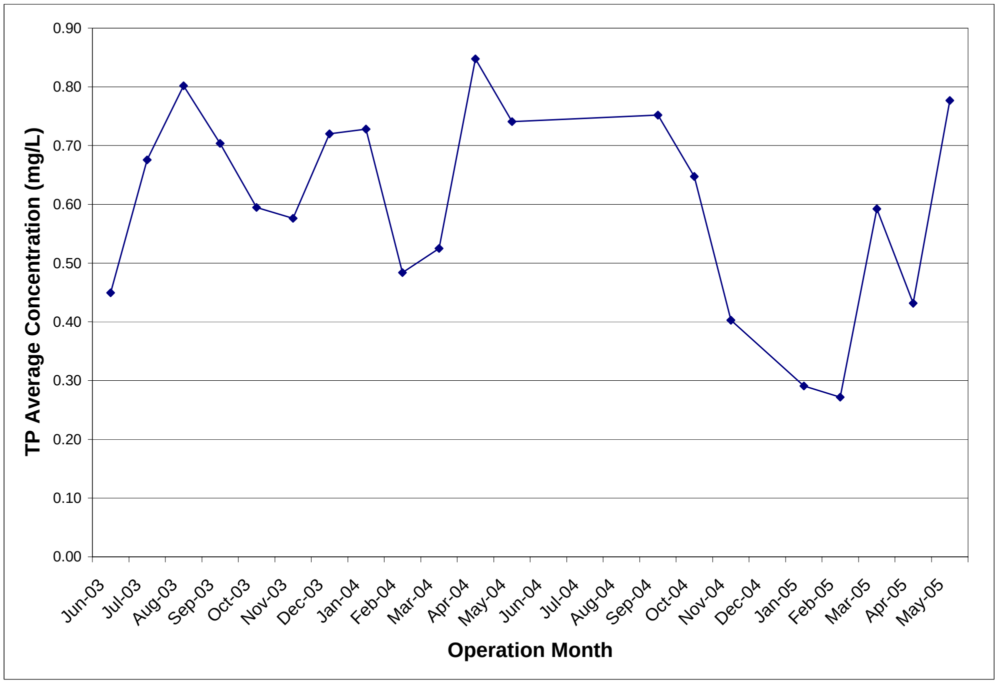

Figure 4.3. Monthly average concentrations for TP across the wetland system. Data were not collected during the months of June 2004 to August 2004 and again in December 2004.

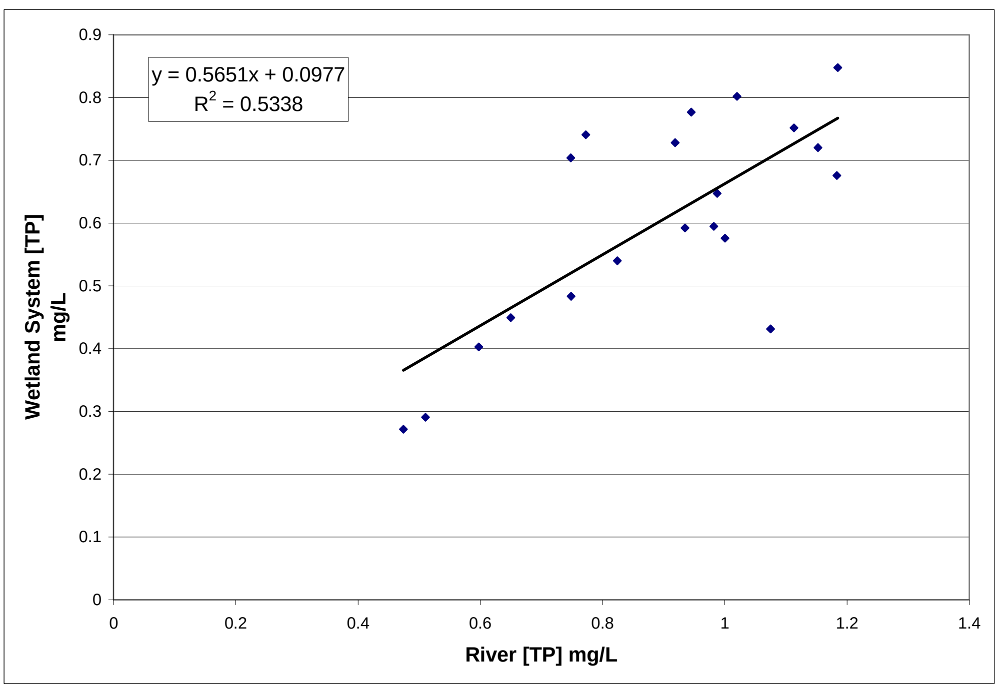

Figure 4.4. Comparison between monthly Trinity River [TP] and wetland system [TP].

Average [TN] for most of the operation months were in the range of 1 to 3-mgL^{-1} (Figure 4.5). Two months (October 2003 and February 2004) dipped slightly below the range, while one month (September 2004) was higher than the range. A comparison among the monthly [TSS] in the wetland system and the Trinity River resulted in a slope of 0.27 and an r^2 of 0.68 (Figure 4.6).

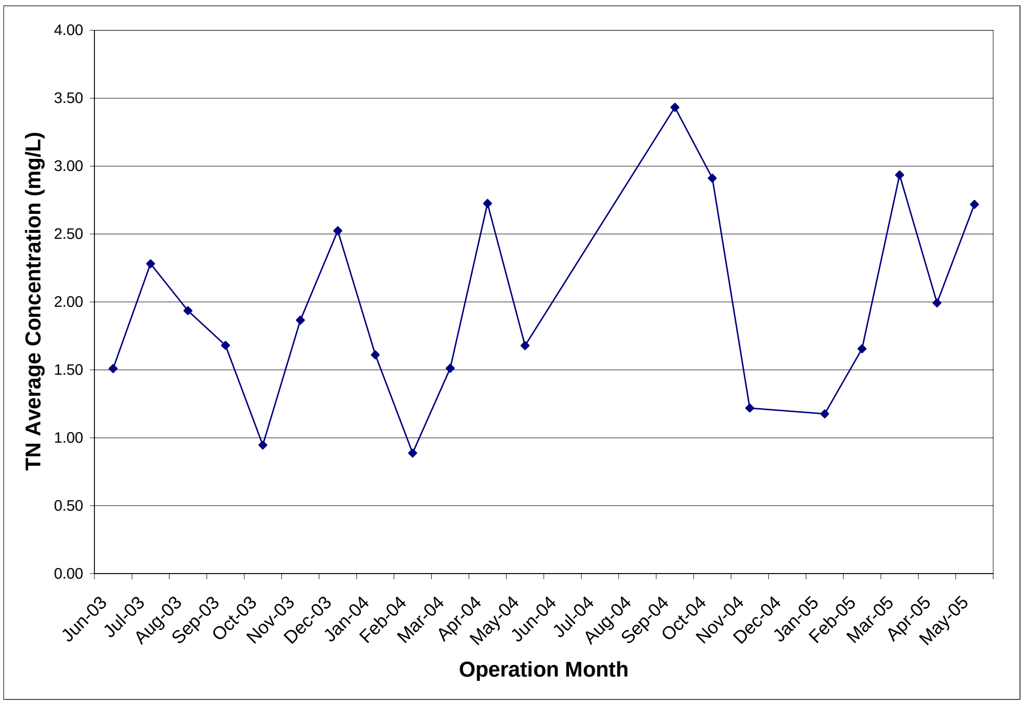

Figure 4.5. Monthly average concentrations for TN across the wetland system. Data were not collected during the months of June 2004 to August 2004 and again in December 2004.

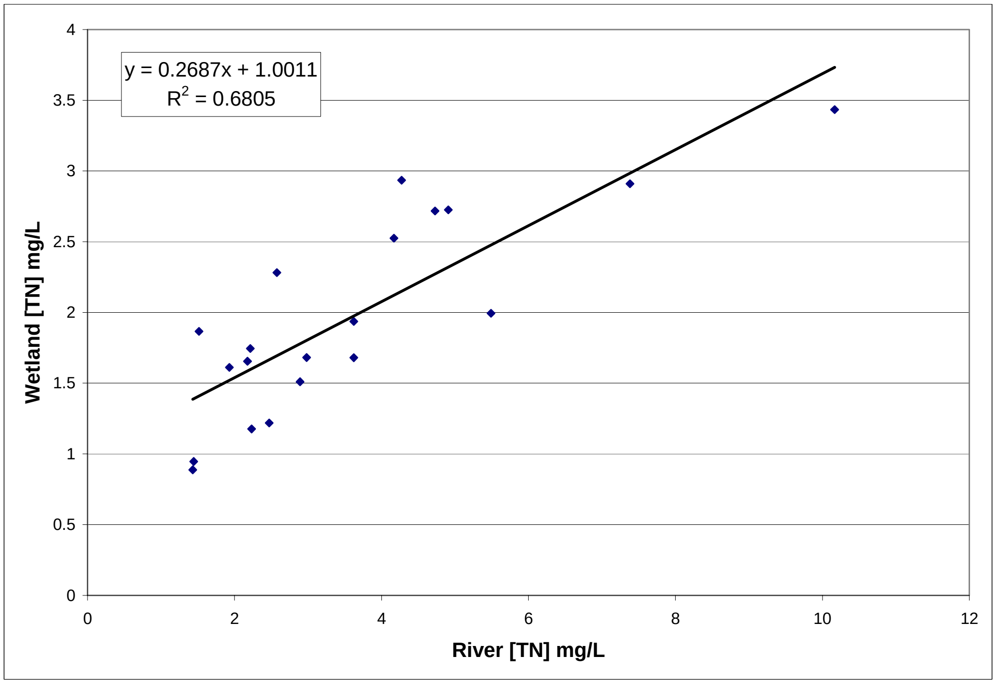

Figure 4.6. Comparison between monthly Trinity River [TN] and wetland system [TN].

4.1.2 Temporal Variability – Seasonal Basis. Seasonal averages for TSS displayed an increasing trend as the seasons progressed (Figure 4.7). The exception was for both winter seasons. TSS levels decreased when going from Fall 2003 to Winter 2003, and then again going from Fall 2004 to Winter 2004.

Average [TSS] for similar seasons (Fall 2003/Fall 2004, Winter 2003/Winter 2004 and Spring 2004/Spring 2005) showed considerable increases in the latter of the like seasons. For instance, mean TSS values for Fall 2004 were higher than the average [TSS] for Fall 2003, at 68.88-mgL^{-1} and 48.74-mgL^{-1}, respectively. Likewise, the average [TSS] for Winter 2004 at 65.48-mgL^{-1} was higher than the Winter 2003 concentration (52.53-mgL^{-1}). [TSS] for Spring 2005 (84.85-mgL^{-1}) were higher than Spring 2004 (70.01-mgL^{-1}).

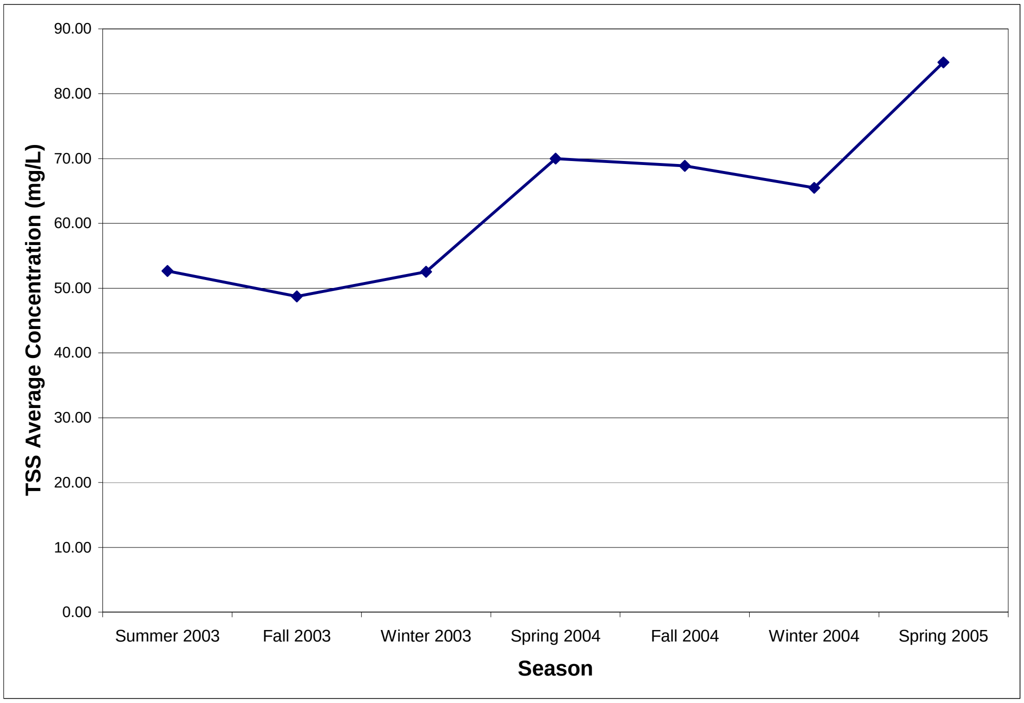

Figure 4.7. Seasonal average concentrations for TSS across the wetland system.

Average seasonal concentrations for TP were roughly the same at approximately 0.62-mgL^{-1} (Figure 4.8). The Winter 2004 season fell considerably short of this seasonal average at only 0.28-mgL^{-1}.

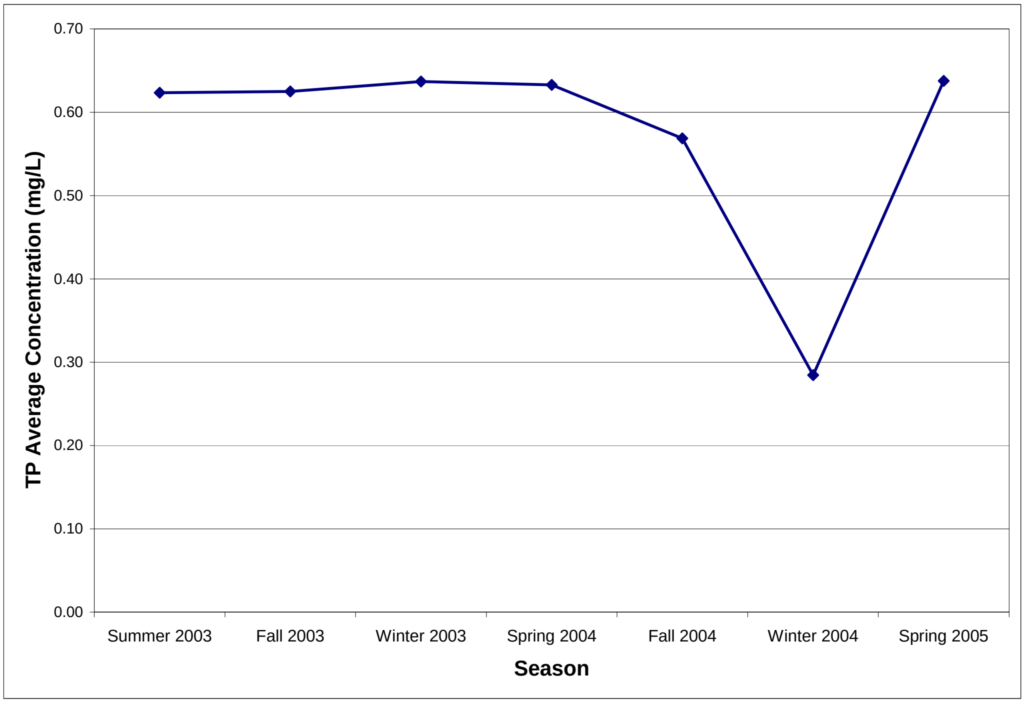

Figure 4.8. Seasonal average concentrations of TP across the wetland system.

Seasonal averages for TN increased on an overall basis (Figure 4.9). Two decreases occurred during the seasonal progression. The first one occurred moving from the Summer 2003 season to the Fall 2003 season. The second decrease occurred between Fall 2004 and Winter 2004.

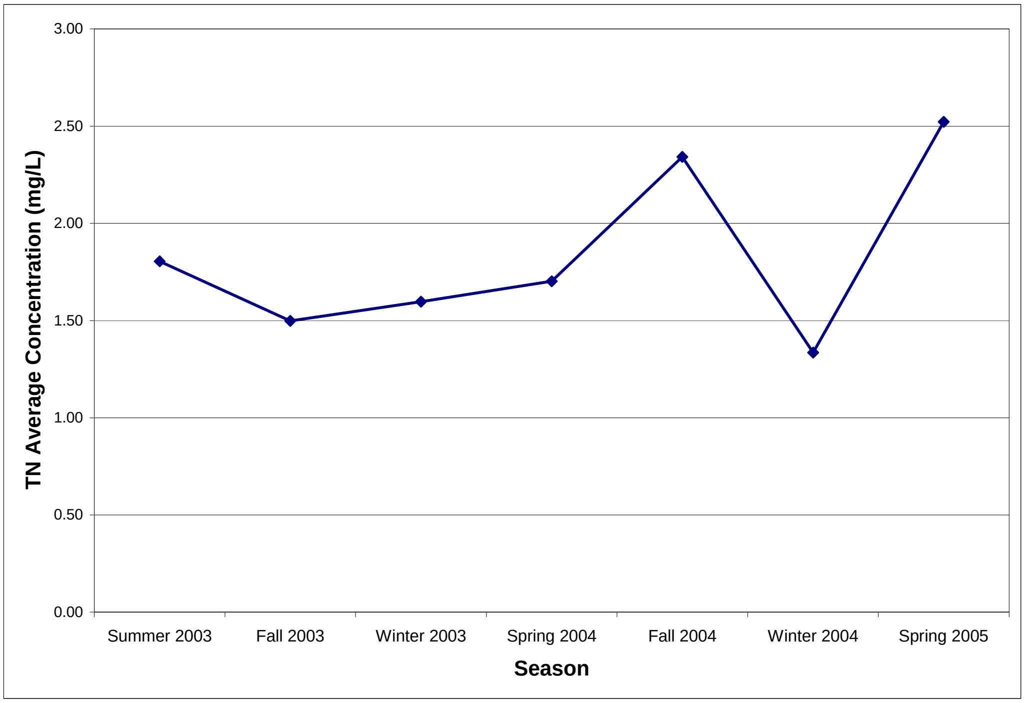

Figure 4.9. Seasonal average concentrations for TN across the wetland system.

4.1.3 Temporal Variability – Yearly Basis. Average yearly concentrations for TSS and TN increased in the second year of operation (Figures 4.10 and 4.12), while the TP concentration decreased (Figure 4.11). Average [TP] was lower in the second year of operation as compared to the first year of operation. The average [TP] in year 1 for the entire wetland system dropped from 0.63-mgL^{-1} to 0.51-mgL^{-1} in year 2. Average [TN] were higher in year 2 (2.10-mgL^{-1}) as opposed to year 1's [TN] (1.64-mgL^{-1}).

The difference in the yearly averages was only significant (t-Test, $\alpha = 0.05$) for [TP] (p-value = 0.039).

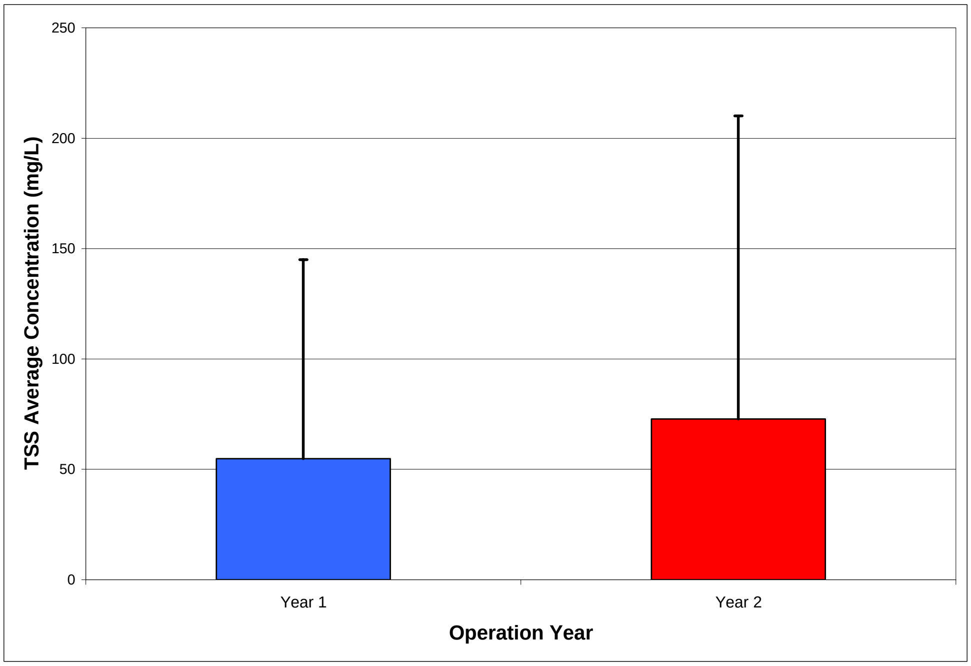

Figure 4.10. Yearly average concentrations for TSS across the wetland system. Bars represent standard deviation.

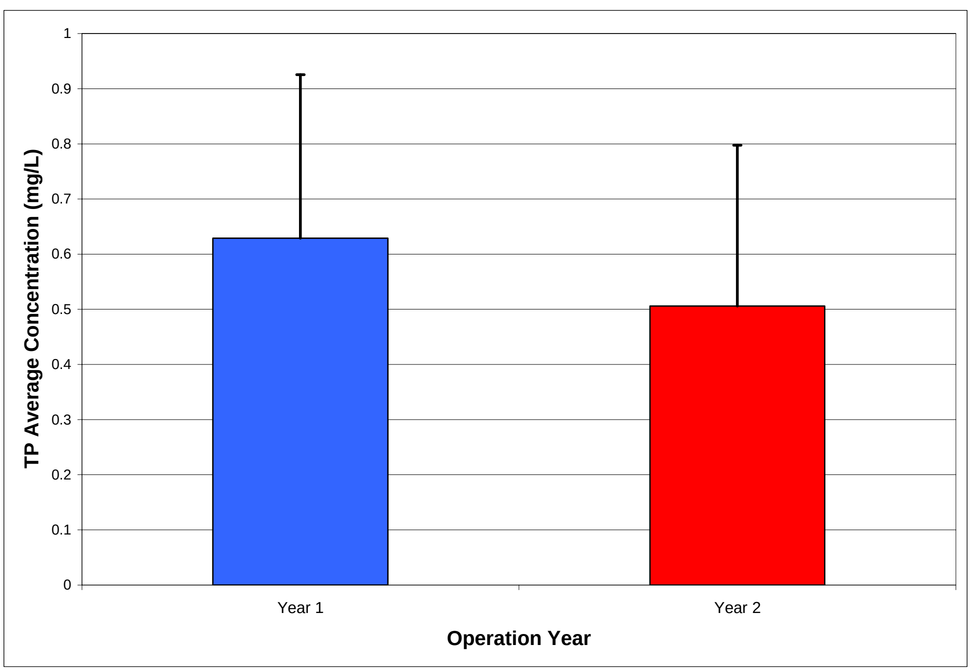

Figure 4.11. Yearly average concentrations for TP across the wetland system. Bars represent standard deviation.

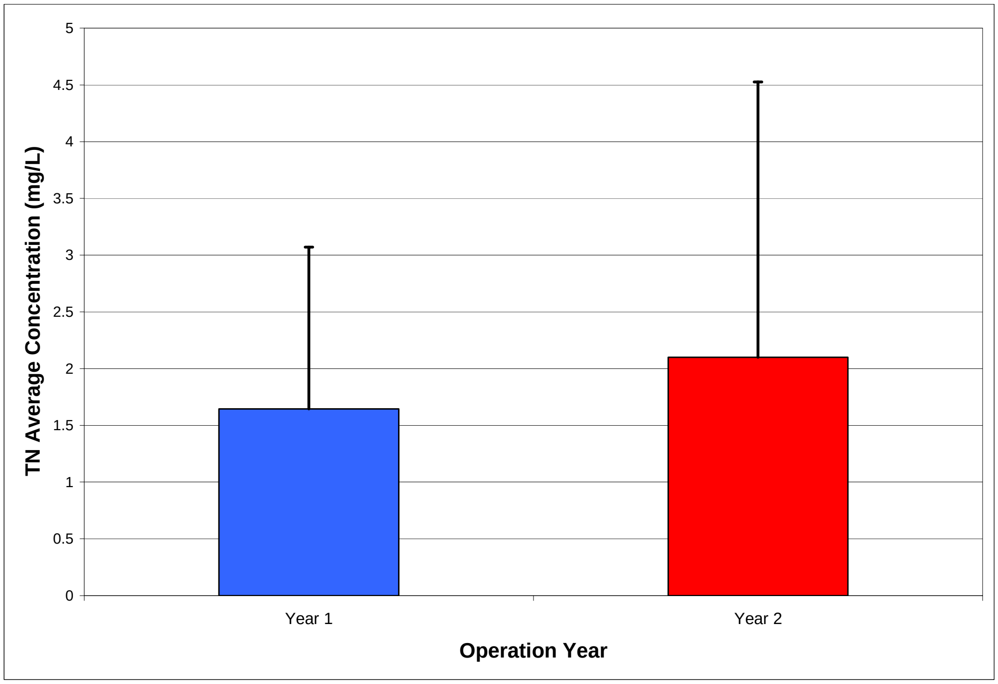

Figure 4.12. Yearly average concentrations for TN across the wetland system. Bars represent standard deviation.

4.1.4 Spatial Variability – Monthly and Seasonal. Monthly and seasonal average concentrations for TSS, TP and TN generally decreased when moving in consecutive order through the field-scale wetland system (Appendix D, Figures D-1 through D-9). For each month in the study, nutrient concentrations for the pump station were normally higher than the average concentration values for the sedimentation basin. This trend continued throughout the four wetland cells. Average nutrient concentrations were generally higher in the first wetland cell as compared to the following three wetland cells.

Average seasonal concentrations were also higher for the initial concentration source (pump station) as opposed to sites located farther from the original source. Occasionally an increase in the average TSS, TP and TN concentrations would occur in one of the wetland cells. For instance, WC4 had the most increases for the three nutrients combined, having a total of seven seasonal increases. In WC4, [TSS] increased during the Winter 2003, Fall 2004 and Winter 2004 seasons; [TP] increased during the

Summer 2003, Spring 2004 and Spring 2005 seasons; and [TN] increased during the Spring 2005 season.

4.1.5 Spatial Variability – Yearly Basis. Looking specifically at the three main constituents, very few increases occurred when moving from site-to-site in consecutive order, not including the Alligator Creek site. Average [TSS] decreased throughout the field-scale wetland system for both years of operation (Figure 4.13). The average [TP] during the second year of operation increased slightly when moving from WC2 to WC3 (Figure 4.14). Similarly, average [TN] increased during the second operational year when going from WC3 to WC4 (Figure 4.15).

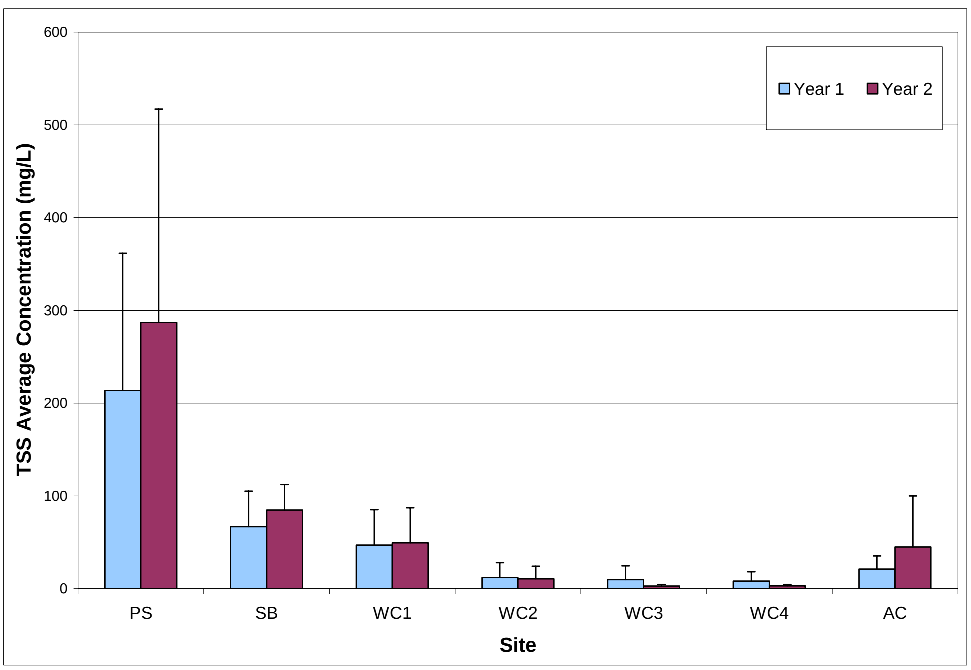

Figure 4.13. Spatial variation of annual [TSS] means. Bars represent standard deviation.

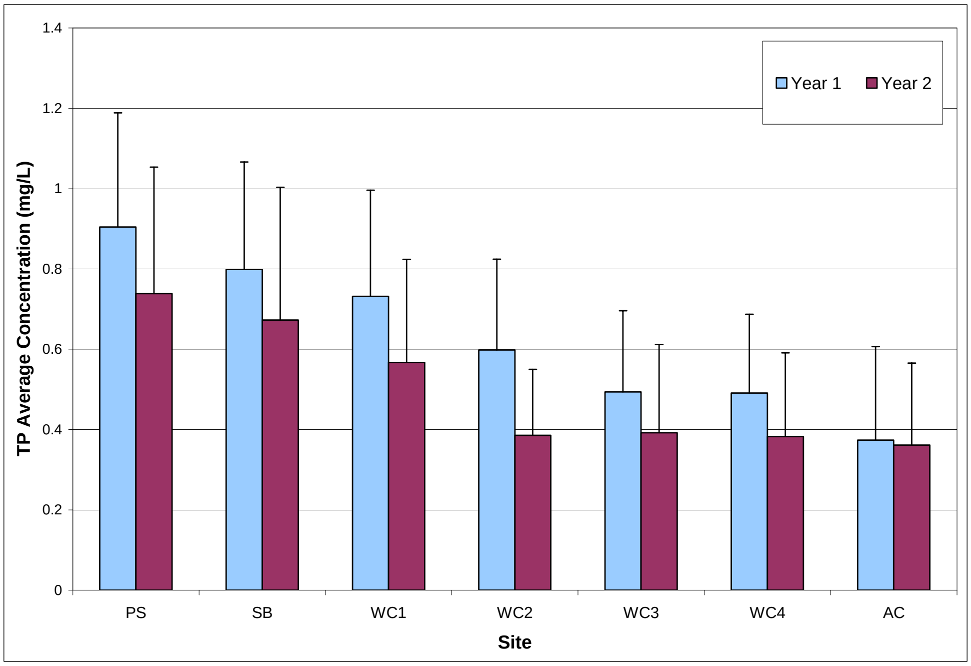

Figure 4.14. Spatial variation of annual [TP] means. Bars represent standard deviation.

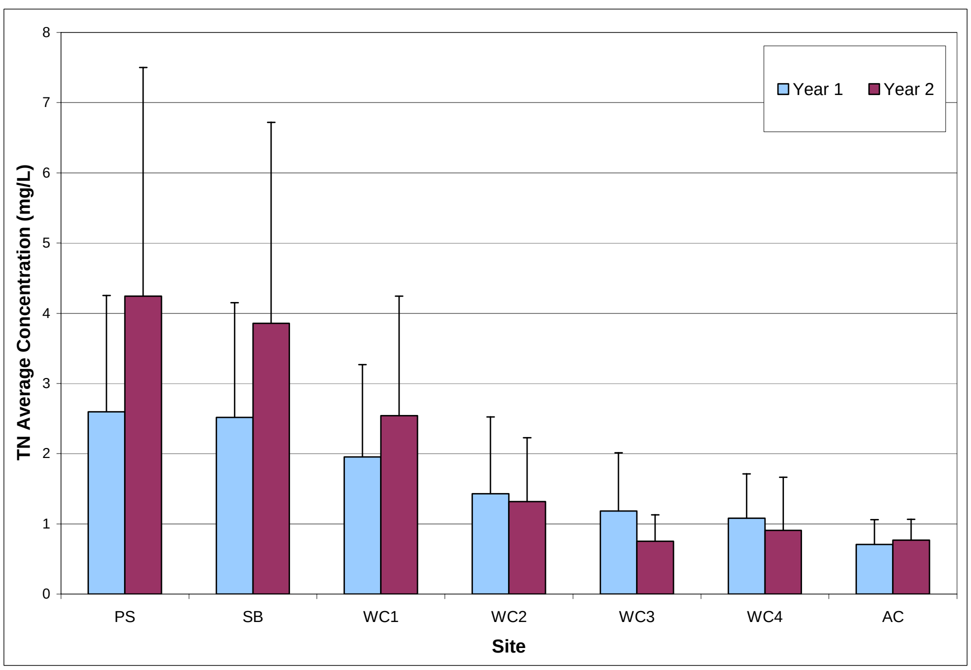

Figure 4.15. Spatial variation of annual [TN] means. Bars represent standard deviation.

Average values for all 17 water quality parameters for year 1 (June 2003 – May 2004) and year 2 (September 2004 – May 2005) were analyzed and it was noted whether the average concentration values increased or decreased for each water quality parameter (Table 4.2). It appears that WC3 was the most effective, in that all of the parameters decreased in their average values. WC2 closely followed with only one parameter increasing in average value from year 1 to year 2.

Table 4.2. Average concentration increases and decreases for each water quality parameter for the entire operation (June 2003 – May 2005).

Yearly Comparisons	Decreases	Increases	Missing Data
PS	11	6	0
SB	9	6	2
WC1	10	5	2
WC2	14	1	2
WC3	15	0	2
WC4	13	4	0
AC	12	5	0

4.2 Correlations

Correlation coefficients were derived for all 17 water quality parameters for the operational period during this study. None of the negative correlations were significant. Therefore, there were no negative coefficients included in the list of significant correlations (Table 4.3). The strongest correlations existed between like parameters (i.e., TSS and TVSS, TP and OP, ALK and HARD). Among the parameters that are not similar in nature, the parameters most strongly correlated were TSS and TURB.

Other relationships with strong correlations included: alkalinity and chlorophyll *a*, hardness and chlorophyll *a*, dissolved oxygen and pH, and chlorophyll *a* and conductivity. Phosphorus in general (both TP and OP) had strong correlations with NOX, TN and conductivity.

TKN, NH3, water temperature and flow were the only water quality parameters that did not have any significant correlations with other parameters. While TKN was not significantly correlated with another parameter, it did contribute to the significant correlations that TN had with other water quality parameters.

Table 4.3. Water quality parameters with significant correlations. Correlations were considered significant if the value was in between 1 and 0.4 or between -1 and -0.4. Numbers in parentheses represent the sample size for the two-year study period.

Correlated Parameters		**Correlation Coefficient**
TSS (432)	TVSS (425)	0.9342
TP (440)	OP (440)	0.9104
ALK (200)	HARD (205)	0.8833
TSS (432)	TURB (369)	0.8328
TVSS (425)	TURB (369)	0.7802
HARD (205)	CHLOR (420)	0.7625
ALK (200)	CHLOR (420)	0.7049
pH (405)	DO (398)	0.5399
OP (440)	COND (404)	0.5072
OP (440)	NOX (433)	0.5049
TP (440)	TN (433)	0.5030
TP (440)	NOX (433)	0.5019
OP (440)	TN (433)	0.5004
CHLOR (420)	COND (404)	0.4658
TP (440)	COND (404)	0.4167

4.3 Percent Reductions

Percent reductions were developed for the field-scale wetland system to determine the removal efficiency of TSS, TP and TN. Reduction calculations were performed for each site within the wetland system, where input and output concentrations were designated to the sites in consecutive order (Table 4.4). Based on these results, WC2 appears to have the highest removal efficiency for all three parameters. SB had the second highest percent reduction for TSS, while WC3 had the second highest removal efficiency for TP and TN. WC4 had the lowest removal efficiency for all three parameters. The two negative values indicate that there was a higher amount of that particular nutrient in WC4 than was found in WC3 (i.e., the output concentration was greater than the input concentration).

Table 4.4. Removal efficiencies of TSS, TP and TN over the entirety of the project (June 2003 – May 2005). These results represent the average percent reductions in concentration for the operational period.

Parameter Removed	SB	WC1	WC2	WC3	WC4
TSS	65.24	31.25	75.91	11.13	-9.64
TP	10.2	11.03	18.86	16.18	2.81
TN	3.37	20.36	28.70	23.87	-0.36

To determine the removal efficiency of each site within the wetland system, the Trinity River concentration was used as the input [x] and each site was used as the output [x]. Once the percent reductions were calculated for each site, the results were then subtracted moving in consecutive order. For instance, the percent reductions for TSS were as follows: PS to SB at 64.96%, PS to WC1 at 75.69%, PS to WC2 at 94.57%, PS to WC3 at 96.29%, and PS to WC4 at 96.88%. These percentages were then subtracted from each other in consecutive order. The subtracted results for TSS, TP and TN are represented in Figures 4.16 - 4.18.

TSS removal was greatest in the SB, followed by WC2. TP removal was greatest at the WC2 location while TN removal was greatest at WC1 and then WC2.

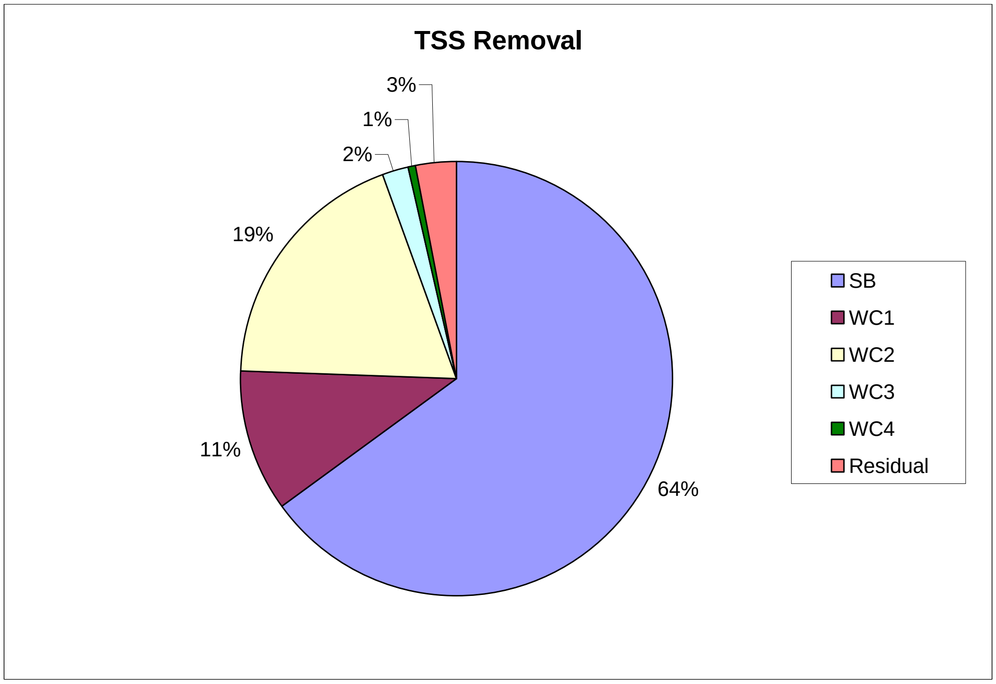

Figure 4.16. Site-by-site TSS removal efficiency of each location within the field-scale wetland system.

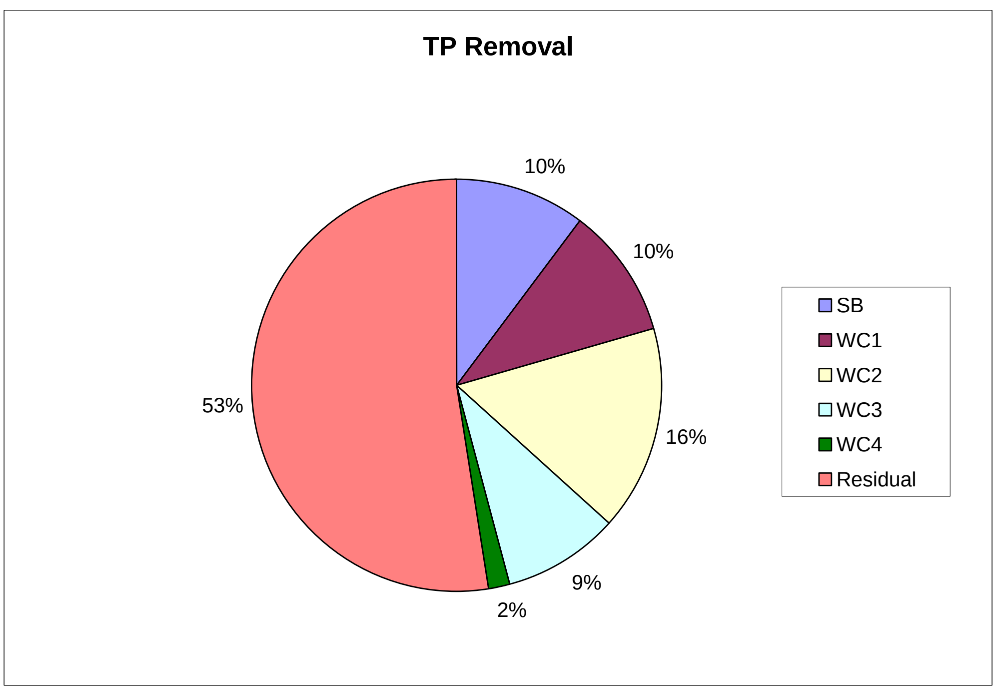

Figure 4.17. Site-by-site TP removal efficiency of each location within the field-scale wetland system.

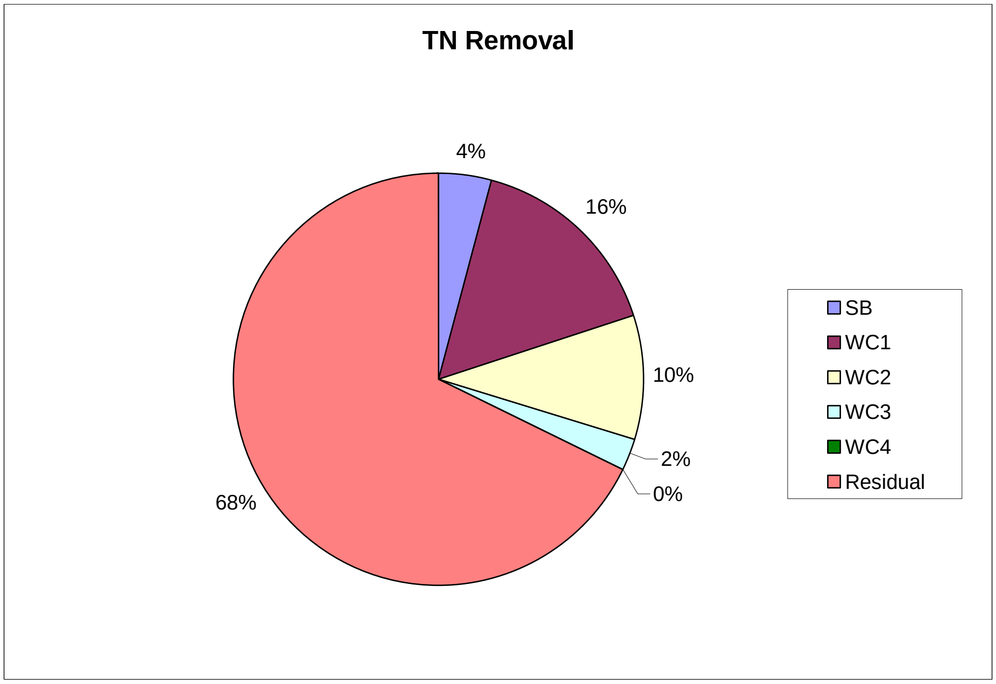

Figure 4.18. Site-by-site TN removal efficiency of each location within the field-scale wetland system.

During the entire time frame of this study (June 2003 – May 2005), TSS removal was significant (t-Test, α = 0.05) in the field-scale wetland system when going from: (1) SB to WC1 (p-value = 0.0022); (2) WC1 to WC2 (p-value = 0.00051); and (3) WC2 to WC3 (p-value = 0.0022). In other words, TSS removal was considered significant as the sites progressed in order, with exception to the final wetland cell (WC4). Completely opposite of TSS, removal of TP in the field-scale wetlands was only significant (t-Test, α = 0.05) when going from WC3 to WC4 (p-value = 0.018). Finally, TN removal was significant (t-Test, α = 0.05) going from SB to WC1 (p-value = 0.035) and then again WC3 to WC4 (p-value = 0.040).

When comparing the two operational years individually, significant removals varied for the three parameters. During the first year, TSS removal was significant (t-Test, α = 0.05) going from SB to WC1 (p-value = 0.0080), WC1 to WC2 (p-value = 0.0026) and then WC2 to WC3 (p-value = 0.0024). TSS removal during the second year was significant (t-Test, α = 0.05) going from WC1 to WC2 (p-value = 0.047) and then

WC3 to WC4 (p-value = 0.014). TP removal was significant (t-Test, $\alpha = 0.05$) going from WC3 to WC4 (p-value = 0.036) during year 1, and then from WC1 to WC2 (p-value = 0.043) during year 2. None of the sites yielded significant removal of TN in the first year, while going from WC1 to WC2 (p-value = 0.030) and then WC3 to WC4 (p-value = 0.017) in the second operational year proved to be significant (t-Test, $\alpha = 0.05$).

Seasonal removal efficiencies of TSS, TP and TN for each site in the wetland system displayed some variability (Table 4.5). It appeared that no consistent pattern exists for the three parameters as they move through the wetland system. For example, when comparing percent reductions for SB and WC1 during the Summer 2003 season, the removal efficiency for TSS, TP and TN decreased, increased and increased, respectively. Similarly, the next season (Fall 2003) displayed an inconsistent pattern among the parameters: TSS decreased, TP decreased and TN increased. In other words, it was more common to find some variation among the three parameters as opposed to having the three parameters' removal efficiencies all increase (or decrease) at the same site.

Likewise, for each individual parameter, there was not a consistent pattern of removal efficiencies increasing or decreasing among the seasons. Out of the three parameters, TP had the most variation among the seasons.

Table 4.5. Seasonal removal efficiencies of TSS, TP and TN at each site in the field-scale wetland system. These results represent the average percent reductions.

	SB	WC1	WC2	WC3	WC4
TSS					
Summer 03	65.39	62.95	81.34	-88.59	41.31
Fall 03	71.82	40.82	87.3	7.83	28.52
Winter 03	65.44	41.46	70.89	56.47	-85.28
Spring 04	66.43	-53.73	72.75	25.63	22.75
Fall 04	68.37	54.69	91.99	29.76	-19.44
Winter 04	64.9	23.12	74.49	86.72	-5.04
Spring 05	82.74	44.81	-4.7	91.24	14.34

Table 4.5. Continued.

	SB	WC1	WC2	WC3	WC4
TP					
Summer 03	1.79	12.73	21.28	37.19	-1.25
Fall 03	25.18	-6.7	10.48	22.38	0
Winter 03	3.31	8.18	39.33	0.99	5.7
Spring 04	11.5	18.76	0.9	-2.18	3.35
Fall 04	8.96	16.8	28.49	7.13	9.28
Winter 04	22.14	12.15	23.29	35.1	2.48
Spring 05	0.81	1.9	26.74	19.1	3.4
TN					
Summer 03	-14.09	36.31	17.78	19.52	46.49
Fall 03	-5.57	1.77	37.32	6.95	0.64
Winter 03	12.59	16.21	18.55	8.95	0.33
Spring 04	9.72	18.94	47.46	11.92	9.1
Fall 04	16.84	52.02	65.45	41.52	-0.43
Winter 04	15.07	5.45	14.44	45.16	5.87
Spring 05	-5.61	16.32	-2.33	71.93	-39.9

The season with the best removal efficiency for TSS and TP was the Winter 2004 season, while TN was removed most efficiently during the Fall 2004 season. Spring 2004 proved to be the worst season for TSS and TP removal, while the lowest percent reduction for TN occurred in Spring 2005.

The overall removal efficiency of TSS, TP and TN was calculated for the operational period for this study, where the Trinity River served as the input concentration and WC4 served as the output concentration (Table 4.6). Dilution effects such as runoff, precipitation and evapotranspiration were not included in the overall removal of these parameters.

The highest percent reduction was for TSS at over 97%. The lowest percent reduction occurred for phosphorus, with removal efficiency just under 50%. Reduction in TN for the field-scale wetlands was approximately 68%.

Table 4.6. Overall removal efficiency of TSS, TP and TN for the two-year study period (June 2003 – May 2005). The input and output concentrations represent the average concentration values for the two-year study.

Parameter	Input Concentration (Trinity River) (mgL^{-1})	Output Concentration (WC4) (mgL^{-1})	Percent Reduction (%)
TSS	238.04	6.43	97.30
TP	0.85	0.45	47.06
TN	3.14	1.02	67.52

4.4 Vegetative Cover

During the field-scale observations for this study, 37 vegetation species were identified throughout the wetland system. A complete listing of all of the vegetation species found throughout the field-scale wetlands is in Appendix E, Table E-1, while vegetation species identified for each individual wetland cell are listed in Appendix E, Tables E-2 through E-5.

4.4.1 Vegetation Richness. Over the course of this study, WCs 1 and 3 supported the greatest richness of vegetation species. Not including the open water classification, both wetland cells had a total of 27 different species. WC4 was next having 24 total species each, while WC2 had the least amount of vegetation richness, only having 16 different vegetation species.

On a survey-to-survey basis, the Summer 2003 supported the greatest richness for the entire wetland system, with 26 different species. The Spring 2004 season closely followed, having 25 different species. The survey containing the least amount of richness was the Winter 2003 season followed by the Winter 2004 season, with 13 and 18 species, respectively.

4.4.2 Vegetation Dominance. Each identified species was assigned a dominance ranking. The sum of these rankings provided the dominance order of the vegetation species present in the wetland cells. While open water is not a valid vegetation classification, it was used when there was scarce vegetation present.

For the entire wetland system, the top three dominance ranks were noted for each survey conducted (Table 4.7). Open water had a strong presence in four out of the six surveys conducted. Duckweed (*Lemna* spp.) was one of the top three dominant species in all but the two winter surveys. Both algae and water primrose (*Ludwigia peploides*) appeared in the top three species in three of the six vegetation surveys.

The sums of the dominance rankings were used to generate cumulative abundance for each of the vegetation species. The cumulative abundance results were then used to compute the percent cover per vegetation species. For each wetland cell, five species that contained the highest percent cover were selected from each of the vegetation surveys. Vegetative cover percentages for these selected species were then combined to create a total percent cover for the combined field-scale wetland cells and for each individual wetland cell (Figures 4.19 – 4.23).

For each wetland cell, open water had the dominant presence. Duckweed was the most prevalent vegetative species throughout the wetland system, followed by algae and water primrose. For WC1, sedge (*Carex* sp.) was the most dominant species, followed by water primrose and duckweed. Duckweed was dominant in WC2, followed by crowfoot sedge (*Carex crus-corvi*) and spiderlily (*Hymenocallis liriosme* (Raf.) Shinners). WC3 was dominated by algae and then by duckweed and burhead (*Echinodorus rostratus* (Nutt.) Engelm.). The dominant species in WC4 was algae, followed by duckweed and water primrose.

Table 4.7. Top three vegetation dominance ranks by season for the field-scale wetland system. Species are listed in order of dominance.

Summer 2003	**Fall 2003**	**Winter 2003**
Lemna spp.	Open Water*	Open Water
Algae	*Lemna* spp.	*Hymenocallis liriosme*
Echinochloa rostratus	*Ludwigia peploides*	*Carex crus-corvi*
Spring 2004	**Winter 2004**	**Spring 2005**
Open Water	Algae	*Lemna* spp.
Algae	Open Water	*Ludwigia peploides*
Lemna spp.	*Ludwigia peploides*	*Echinochloa crus-galli*

*This classification indicates that no particular vegetation species was dominant, thus the area was designated as open water.

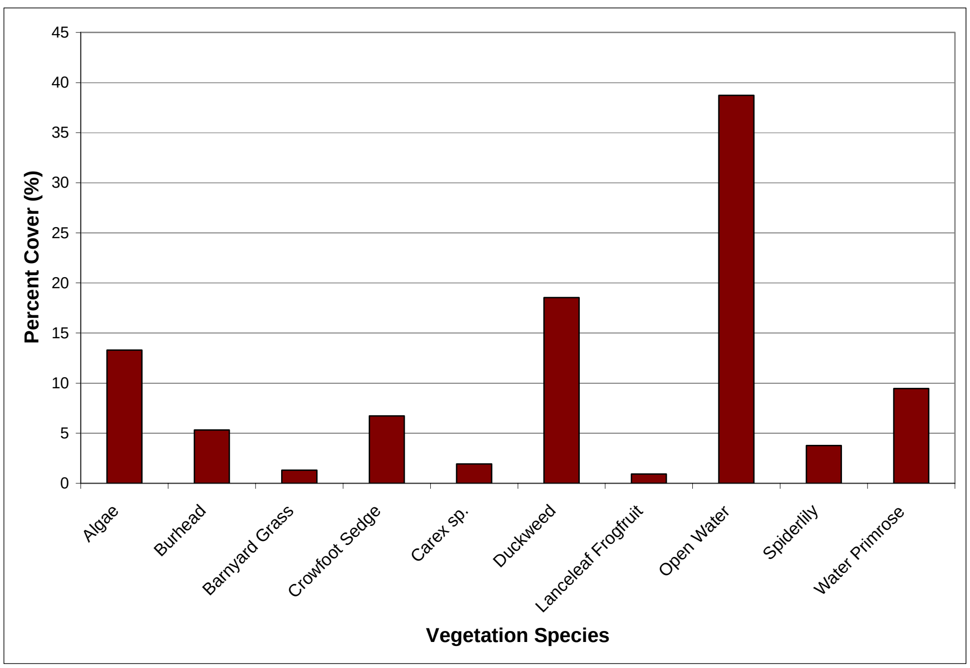

Figure 4.19. Percent cover of vegetation species for the field-scale wetlands. These are the most abundant vegetation species from all of the seasonal surveys combined for all of the wetland cells.

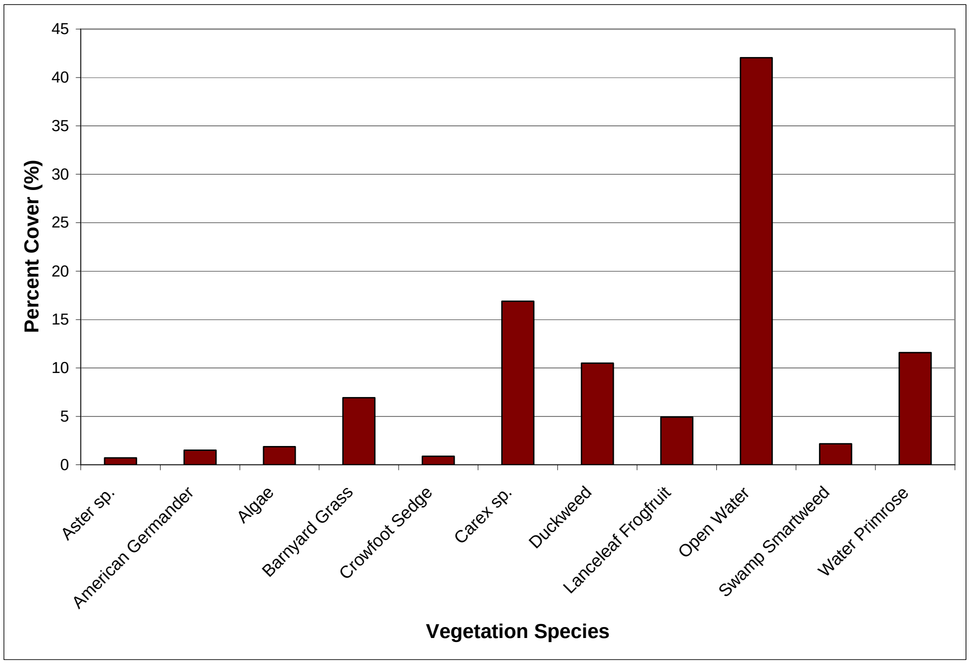

Figure 4.20. Percent cover for vegetation species in wetland cell 1. These are the most abundant vegetation species from all of the seasonal surveys combined for WC1.

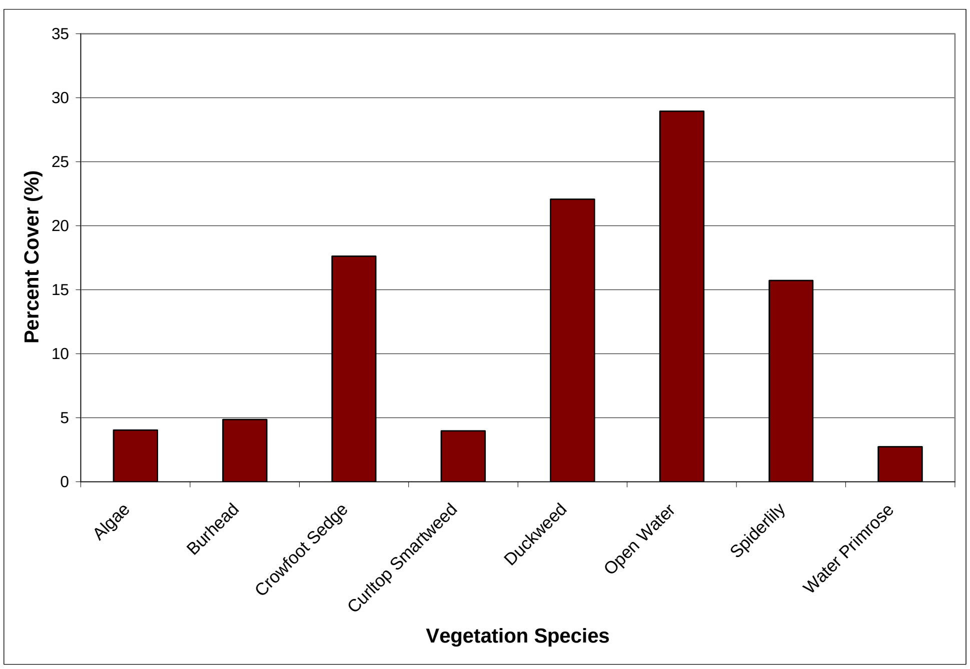

Figure 4.21. Percent cover for vegetation species in wetland cell 2. These are the most abundant vegetation species from all of the seasonal surveys combined for WC2.

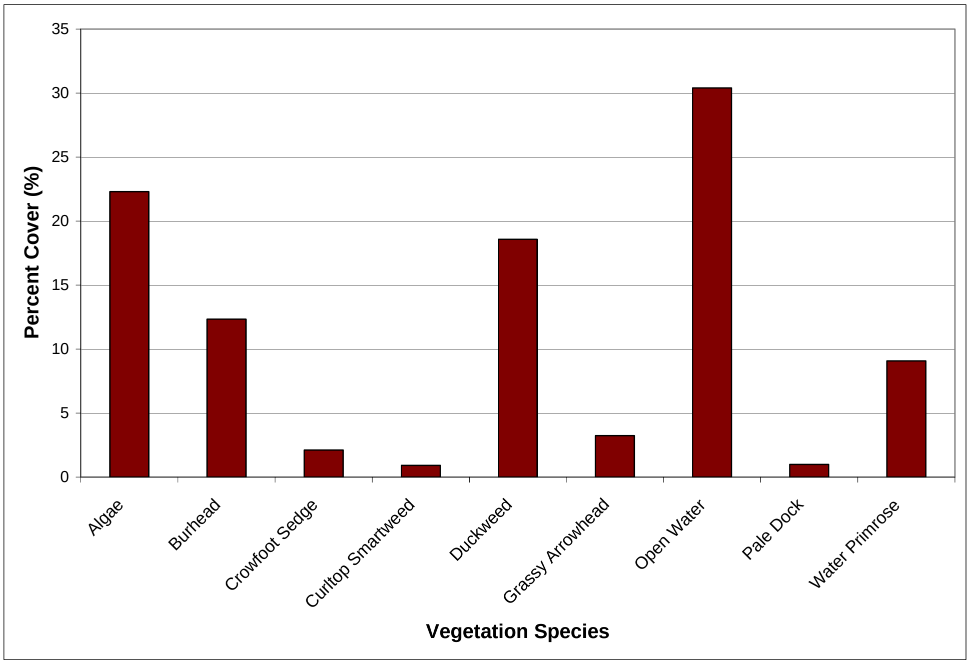

Figure 4.22. Percent cover for vegetation species in wetland cell 3. These are the most abundant vegetation species from all of the seasonal surveys combined for WC3.

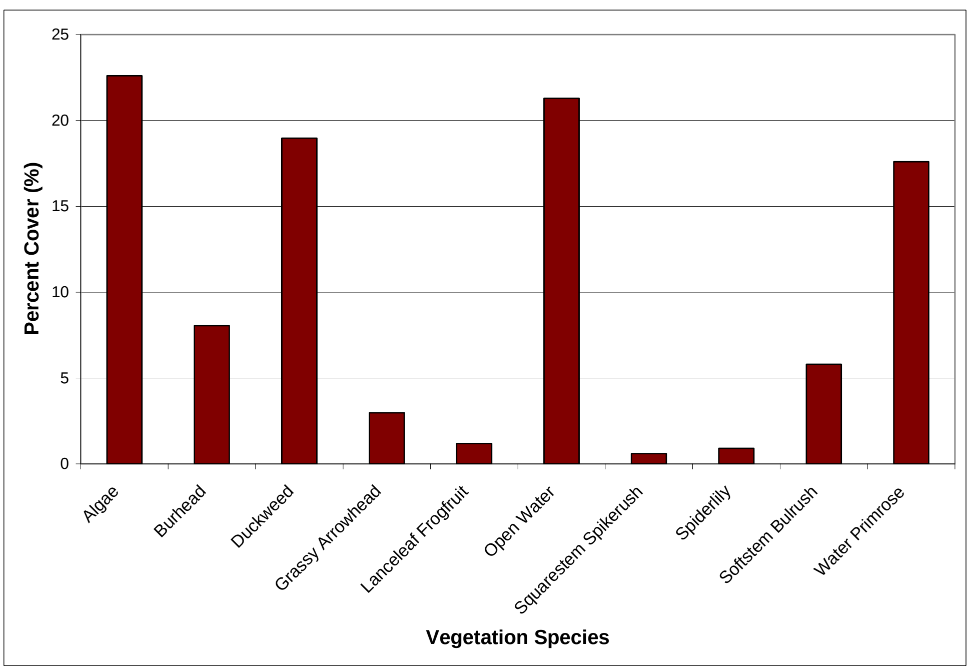

Figure 4.23. Percent cover for vegetation species in wetland cell 4. These are the most abundant vegetation species from all of the seasonal surveys combined for WC4.

4.4.3 Vegetation Composition. Each wetland cell was composed of different types of vegetation species that comprised four main categories: submerged, floating, emergent and terrestrial. The number of submerged and floating species was similar for all four wetland cells, while the amount of emergent and terrestrial had more variation among the cells. WC1 had three submerged species, two floating species, 12 emergent species and ten terrestrial species. WC2 had three submerged, two floating, six emergent and five terrestrial species. WC3 was made up of two submerged species, three floating species, 12 emergents and ten terrestrial species. WC4 had two types of submerged species, two floating species, nine emergents and 11 terrestrial species.

4.5 Removal Efficiency versus Vegetation

4.5.1 Nutrient Removal and Vegetation Richness. WC2 had the best removal efficiency of TSS, TP and TN, all the while having the least amount of vegetation richness. WC4 had the lowest removal efficiency of all three parameters, but had the greatest richness of vegetation species.

The Winter 2004 season had the best removal efficiency of TSS and TP, while the Fall 2004 season proved to remove TN most efficiently. Each of these seasons were low in species richness. The Spring 2004 season had the lowest removal efficiency for TSS and TP, and the Spring 2005 season had the lowest TN removal. The amount of species richness for these two seasons was the second and third highest among the vegetation surveys. Basically, the same pattern exists for the seasonal analysis as does the cell-by-cell analysis: the higher the nutrient removal, the lower the vegetative species richness and vice versa.

4.5.2 Nutrient Removal and Vegetation Dominance. In addition to richness, vegetative dominance was also taken into consideration when addressing the removal efficiency. Duckweed dominated WC2 (the cell with the best removal efficiency of TSS, TP and TN), while algae was the dominant species in WC4 (had the worst removal efficiency of the three parameters). WC3 was dominated by algae, as well, but that cell proved to have the second best removal efficiency of TP and TN. WC1 largely consisted of *Carex* sp. and proved intermediate removal efficiency for the three parameters.

Out of the top three species in WC2, only one of them appeared as a top three abundant species in at least one other cell. Duckweed was among the top three species for all four wetland cells, but at different percentages. WC2 had the highest percentage of duckweed (over 100%), while it occurred at a similar percentage for WCs 3 and 4 at more than 80% and 90%, respectively, and at a much lower percentage (just over 50%) for WC1.

4.5.3 Nutrient Removal and Vegetation Composition. Nutrient removal efficiency of the three parameters generally followed the same pattern for all of the wetland cells: WC2 had the best removal efficiency, while WC4 had the worst. The only difference between the parameters was which cell came after WC2. For TSS, WC1 followed WC2, while WC3 came next after WC2 for TP and TN.

While WC2 had the best nutrient removal efficiency, it had the least amount of top vegetative species (Figure 4.21) and the least amount of emergent and terrestrial species (Appendix E, Table E-3). WC4, the cell with the worst removal efficiency, had the second highest number of top vegetative species (Figure 4.23), as well as had the second highest amount of emergent and terrestrial species (Appendix E, Table E-5) .

4.6 N:P Ratios

N:P ratios were calculated for each site within the field-scale wetland system (Table 4.8). The N:P ratios generally decreased moving site-to-site in consecutive order. There was a slight increase in N:P ratio going from the Trinity River to the SB; however, the remainder of the sites experienced decreases.

Table 4.8. N:P ratios (based on molar concentrations) for each site within the field-scale wetland system.

Site	N:P Ratio
PS	1.7:1
SB	1.8:1
WC1	1.4:1
WC2	1.2:1
WC3	1.1:1
WC4	1:1
AC	0.9:1

4.7 Moist-Soil Management

Mean concentration values and percent reductions were recorded for the two start-up periods before and after moist-soil management (Table 4.9). Average [TSS] for the original start-up period was higher than the start-up period after the moist-soil management was initiated. On the other hand, [TP] and [TN] were lower in the initial stages than they were after moist-soil management was implemented. Likewise, percent reductions improved for TP and TN after moist-soil management, while the removal efficiency was better for TSS before the wetlands were moist-soil managed.

Table 4.9. Average concentrations and percent reductions before and after moist-soil management. Standard deviation follows the "±" sign.

Parameter	Average Concentration (mgL^{-1})	Percent Reduction (%)
June 2003		
TSS	74.08 ± 113.56	99.46
TP	0.45 ± 0.29	-33.33
TN	1.51 ± 1.37	65.08
Sept and Oct 2004		
TSS	71.68 ± 150.60	96.74
TP	0.67 ± 0.27	61.73
TN	3.02 ± 3.77	93.38

4.8 Pilot-Scale versus Field-Scale Wetland Systems

Removal efficiencies for TSS, TP and TN were similar for both wetland systems. Out of the three parameters, TSS had the highest removal in both the pilot-scale and field-scale wetlands, at 95% and 97% removal, respectively. TN had the next highest removal efficiencies (80% for pilot-scale wetlands and 68% for field-scale wetlands), while TP reduction was the lowest in the two systems (65% and 47% pilot-scale and field-scale, respectively).

In the pilot-scale system, TN and TP were removed most efficiently in train 2 (contained wetland cells 4 through 6) (APAI 2002). The overall removal of TSS was reported for the pilot-scale wetlands; however, it was not mentioned what train or cell yielded the greatest removal of TSS. In the field-scale wetlands, WC2 had the best removal efficiency of all three parameters.

V. DISCUSSION

5.1 Average Concentrations

5.1.1 Temporal Variability – Monthly Basis. Monthly TSS, TP and TN concentrations appeared to be correlated with average TSS, TP and TN levels in the Trinity River. Monthly averages for TSS were generally in the same range, with the exception of September 2004 and March 2005. The former month was lower than the range, while the latter was much higher. One possible reason for the low value is that the TSS level in the Trinity River on 27 September 2004 (61-mgL^{-1}) was considerably lower than the average [TSS] for the river (225-mgL^{-1}). Therefore, the TSS levels flowing through the wetland system would have been less than they normally were.

Regarding the month with the higher value, the pump station at the Trinity River reported unusually high TSS amounts at 908-mgL^{-1} on 30 March 2005. The average [TSS] for the Trinity River is 225-mgL^{-1}. This spike in TSS was probably due to rainfall that occurred upstream. This most likely led to a run-off event, thus increasing TSS and turbidity levels in the Trinity River (Mr. Darrel Andrews, TRWD, *personal communication*).

Monthly averages for TP were quite variable, but most of the values fell within a particular range. Two months (January and February 2005) were lower than the given range. [TP] were likely lower in these two months because the average [TP] in the Trinity River during these two months was less than the average [TP] reported for the Trinity River during the two-year operational period. Average river [TP] for January and February 2005 were at 0.50-mgL^{-1}, while the average [TP] for the Trinity River was approximately 0.85-mgL^{-1}.

Another possible reason that the average [TP]] was lower in January and February of 2005 was because the average flow during these two months for the wetland system were slightly higher than the average flow levels for the operational period during this study. The average flow reported for January and February of 2005 was

48,673-m^3d^{-1}, while the average flow levels for the study was 47,174-m^3d^{-1}. Kadlec (2005) reported that P movement in wetlands is influenced by hydrologic processes and that surface water movement is the basis for advective transport of P in and out of wetlands. It is possible that the higher flow levels resulted in less TP in the system in that the higher flow moving through the wetland system transported TP faster, and hence there was less TP to be measured.

Average monthly [TN] fluctuated with the average river [TN].
During the study period, the TN levels in the Trinity River averaged 3.14-mgL^{-1}. The average river [TN] for the months of October 2003 and February 2004 were at 1.44-mgL^{-1} and 1.43-mgL^{-1}, respectively. Similarly, average river [TN] was considerably higher for the month of September 2004, at 10.17-mgL^{-1}.

From the regression analyses, [TSS] had the best match between river concentrations and what is found in the field-scale wetland system, followed by [TN] and lastly [TP].

5.1.2 Temporal Variability – Seasonal Basis. Seasonal river concentrations tended to guide seasonal levels of TSS, TP and TN in the field-scale wetlands. Additionally, increased TSS levels in the Trinity River may be attributed to increased rainfall either in the local area near the wetland system or in an area upstream of the wetlands. Monthly precipitation data were collected from the National Climatic Data Center for Navarro and Freestone counties. Precipitation levels varied as the seasons succeeded in order; however, average precipitation levels increased from year 1 to year 2. These higher precipitation levels might be correlated with the higher TSS levels in the Trinity River, and thus in the field-scale wetland system.

Another explanation as to why the TSS levels were higher as the seasons progressed is simply having more vegetation in the wetland system. As vegetation becomes more established as the wetlands mature, vegetative detritus accumulates in the sediment. As the seasons progress, there should be more dead plant matter to take into account. The vegetative detritus adds more TSS to the system (Karathanasis et al. 2003).

In the seasonal analysis of TP, there was a sharp increase in average concentration from the Winter 2004 season to the Spring 2005 season, where the average [TP] increased from 0.28-mgL^{-1} to 0.60-mgL^{-1}. This increase may be attributed to vegetation. Plant uptake and storage is a major removal mechanism of P in wetlands; however, storage is only temporary. Nutrients, such as P, are released to the water and sediments when the plants die (Richardson 1985, Mitsch and Gosselink 2000, Kadlec and Reddy 2001, McCarey et al. 2004). This generally occurs in the autumn and winter months, and as a result, P concentrations tend to be higher in the spring months (McCarey et al. 2004). Hence, this may explain why an increase occurred between these two seasons.

As with the seasonal [TP], the average [TN] in the Winter 2004 season were lower than the other seasons. Colder water temperatures might have been a factor in the lower [TN] (Ran et al. 2004). The average temperature during the two-year study period was 21.11-°C, while the average water temperature for the Winter 2004 season was 11.96-°C.

5.1.3 Temporal Variability – Yearly Basis. Yearly concentrations of TSS, TP and TN in the field-scale wetlands appeared to be directly related to the river concentrations of these three parameters. When the river levels increased, the wetland system levels increased. Likewise, when the river concentrations decreased, the field-scale wetlands displayed a decrease in the average parameter levels.

The average [TSS] for the Trinity River during the first year of operation was approximately 210-mgL^{-1}. This average increased to 300-mgL^{-1} during the second operational year. Similarly, the wetland system as a whole experienced an increase in [TSS] from year 1 to year 2.

Lower [TP] during the second operational year in the Trinity River might explain the decrease in TP levels in the wetland system. The average [TP] in the Trinity River for the second year was 0.74-mgL^{-1}, while the average [TP] for the first year was 0.90-mgL^{-1}.

It appears that the average [TN] in the Trinity River dictated the amount of TN found in the wetland system on an annual basis, as well. Average river [TN] increased from 2.60-mgL^{-1} in the first operational year to 4.24-mgL^{-1} in the second year.

5.1.4 Spatial Variability. Average [TSS], [TP] and [TN] generally followed the same pattern for monthly, seasonal and yearly analyses: average concentrations usually decreased when moving from site-to-site in the wetland system. Similar findings were reported by Cameron et al. (2003), where sediment and plant uptake analyses indicated that N and P concentration levels were higher in the first of two wetland cells. Likewise, Cameron (2001) referenced another study where P concentrations were higher in the first wetland cell in a series of connected cells.

It was not uncommon for the average nutrient values to increase in the final site (Alligator Creek). Higher [TSS] may be attributed to storm water flow, while higher [TP] and [TN] are likely due to the agricultural runoff that enters Alligator Creek upstream of the final water quality measuring site (Mr. Darrel Andrews, TRWD, *personal communication*).

5.2 Correlations

The strongest correlation that existed among the parameters, not including the correlations between similar parameters, was for TSS and turbidity. Dodds and Whiles (2004) also found a strong correlation between TSS and turbidity. Turbidity refers to how clear the water is. Hence, the more TSS in the water the cloudier the water appears and the more turbid the water is.

The measure of alkalinity refers to the water’s ability to resist change in pH (Murphy 2005). Chlorophyll *a*, which is key to photosynthesis, is the green pigment found in plants. Cole (1994) pointed out that there are interrelationships among various forms of photosynthesis and pH. It can be inferred that changes in the photosynthesis process, namely chlorophyll *a*, result in pH changes and thus cause changes in alkalinity.

Phosphorus and nitrogen are essential to all life and have been shown to be vital nutrients to a wetland's biogeochemistry (Cole 1994, Mitsch and Gosselink 2000). The relationship between the two nutrients is well understood (Mitsch and Gosselink 2000).

5.3 Percent Reductions

Nutrient removal is composed of a combination of physical and chemical processes. For instance, the main removal pathways for nitrogen and phosphorus are by sedimentation, accumulation by plants and microorganisms, or denitrification (for nitrogen) (Hemond and Benoit 1988, Saunders and Kalff 2001). Day et al. (2004) pointed out that sedimentation combines numerous removal processes including: the settling of organic and inorganic matter in the water column, microbial uptake and the incorporation of organic matter into the sediment matrix. Plant accumulation offers a short-term storage of nutrients in that the nutrients will likely be released back into the wetland system when the plants die (Richardson 1985, Hemond and Benoit 1988, Mitsch and Gosselink 2000, Kadlec and Reddy 2001, McCarey et al. 2004). Denitrification has been shown to be the primary pathway for TN retention (DeBusk et al. 1983, Saunders and Kalff 2001). While vegetation has been shown to increase TSS retention by decreasing resuspension of sediment particles (Kadlec and Knight 1996, Braskerud 2001), TSS removal is mostly a physical settling and filtration process (Karathanasis et al. 2003).

The goals of the present study did not include determining which process (biological, chemical or physical) occurred or how significant the process was. Instead, the field-scale wetlands' ability to efficiently remove nutrients was analyzed.

Removal of TSS was more significant in the earlier stages of the wetland system, while TP removal was more significant in the end of the wetland system. Steer et al. (2005) found TSS removal to be more efficient in the first of two connected wetland cells, while reduction in TP was the result of both cells taken together. TN had significant removal at the very beginning of the wetland system (going from SB to WC1) and then at the very end (WC3 to WC4).

Seasonal removal of TP and TN in the field-scale wetlands varied and often differed from past studies. The highest removal of TP in the winter is problematic to explain. Steer et al. (2002) found that single-family constructed wetlands in Ohio provided the least removal efficiency for TP in the winter and that the best efficiency was found in the fall season. McCarey et al. (2004) also found that the fall had the most phosphorus removal and attributed this to senescing plants releasing P into the wetland system. While Ran et al. (2004) claimed there was a correlation between P removal and water temperature, Kadlec and Knight (1996) stated that temperature had no significant effect on P retention in either north temperate or subtropical wetlands. Kadlec and Reddy (2001) suggested that P removal was a result of a physical process, such as settling, rather than being temperature-dependent.

TN removal is driven by its components (i.e., TKN and NOX) and thus integrates a number of processes and constituents (Kadlec and Reddy 2001). Therefore, claiming that TN was removed most efficiently in the Fall 2004 season is essentially saying that its components had the best removal efficiency in the fall. A number of studies have reported higher TN removal rates in warmer seasons (Spieles and Mitsch 2000, Ran et al. 2004, Toet et al. 2005). Fall temperatures in Texas are usually comparable to summer and spring temperatures; therefore, water temperatures in the field-scale wetlands during the fall season are similar to the warmer seasons. In fact, the average water temperature for the field-scale wetland system during the Fall 2004 season was 21.21-°C, just above the overall average of 21.11-°C. This may help to explain why the fall season had the highest TN removal efficiency.

The two spring seasons resulted in the worst removal efficiency of the three parameters. Mitsch and Gosselink (2000) point out that less nutrient retention is brought about during the spring, suggesting that cold weather leads to diminished microbial activity in the water column and sediments, thus slowing down processes.

High overall removal efficiencies for TSS, TP and TN were displayed by the field-scale wetland system (PS to WC4). According to Cameron's (2001) review of past literature, treatment wetlands remove approximately three quarters of the incoming TSS, provided the incoming TSS is greater than 20-mgL^{-1}. Further review indicates that TSS concentrations may be reduced to values of 5 to 15-mgL^{-1} by wetlands serving as secondary treatment (Cameron 2001). Based on the results of the TSS output levels, it is apparent that the field-scale wetlands are efficient as treatment wetlands.

A review of past studies reported that phosphorus removal in constructed wetlands is highly variable (Hunter et al. 2001), and that constructed treatment wetlands have demonstrated low removal efficiencies of phosphorus (Kadlec 2005). Phosphorus removal in wetlands is higher in the initial stages of operation; however, removal efficiency tends to decrease as time goes by and the system matures (Mann 1990, Kadlec and Knight 1996, Kadlec 2005). Based on this information, it is difficult to determine if the field-scale wetlands are efficient in their removal of TP.

Brix (1994) found that removal of TN in free-surface wetlands is often greater than 50%. As previously mentioned, the TN measurement is the result of NOX and TKN combined; therefore, a reduction in TN is actually a reduction in the parameters it is comprised of. Kadlec (1994) reviewed several treatment wetland systems and found that the removal efficiencies of NOX and TKN were quite variable, ranging from -138 - 96% for NOX and 3 - 98% for TKN. The percentage of TN reduced by the field-scale wetlands fell comfortably within these ranges.

5.4 Removal Efficiency versus Vegetation

Plants play an important role in a wetland's ability to remove nutrients. Hemond and Benoit (1988) suggested that plants are the primary source of chemical reducing capacity in wetlands. Research in the past has found that 16 - 75% of TN removal and 12 - 73% TP removal can be attributed to plant uptake (Reddy and DeBusk 1987). Mitsch and Gosselink (2000) mention a number of plants that can be effective in treatment wetlands, especially with regards to plant uptake. Ideal plant species would have rapid nutrient uptake and provide a greater duration of nutrient storage (Reddy and DeBusk 1987). Plants such as *Typha* sp., *Phragmites* sp., *Scirpus* sp., *Panicum* sp., *Pontederia* sp. and *Sagittaria* sp. have shown great potential to be effective in treatment wetlands because of their nutrient uptake and storage capabilities (Reddy and DeBusk 1987).

Not only are wetland plants major storage units for nutrients, they promote sedimentation. Brueske and Barrett (1994) found that wetland vegetation can directly influence sediment deposition. While the importance of wetland vegetation is noted, it is important to recognize that nutrient removal through plant uptake eventually reaches a point where no additional uptake can occur. When this happens, other factors (i.e., hydraulic load and sediment load) come into play and have a greater influence on the nutrient retention than the vegetation does (Braskerud 2001).

In the present study, plants are treated as the primary mechanism for nutrient removal. Retention performance is based on vegetation variety, composition and dominance.

5.4.1 Vegetation Dominance. Not only was duckweed the most abundant species in WC2, it is the most documented species out of the three. Hillman and Culley (1978) found that duckweed exhibited rapid growth rates in nutrient-rich environments. Duckweed is able to remove nutrients, such as nitrogen and phosphorus (Reddy and DeBusk 1987, Vymazal 2002); however, Ran et al. (2004) pointed out that duckweed has a limited ability to efficiently remove N and P through plant uptake. Duckweed, a floating aquatic plant, grows only in the upper water surface layer; therefore, duckweed can only remove nutrients from this particular area within the water column. In order to get a more thorough removal efficiency of the entire water column and sediment, a combination of several types of plants, such as floating, submerged and emergent, should be used (Ran et al. 2004).

Crowfoot sedge and spiderlily were the next most abundant species in WC2. While few if any past studies have been conducted specifically on crowfoot sedge, there are studies that address other types of sedges. Previous works indicate that a carex species was suitable for water treatment (Browning and Greenway 2003) and removed nutrients at an intermediate level (Fraser et al. 2004), while Picard et al. (2005) found that carex was the least efficient species in the study. Generally speaking, carex species are fast-growing, quickly established and process a high amount of energy (Fraser et al. 2004). Similar to crowfoot sedge, little to no work has been done specifically on this particular species of spiderlily. Crowfoot sedge is an emergent plant that typically grows in shallow water, while spiderlily is terrestrial and is typically found along the wetland's shoreline.

5.4.2 Nutrient Removal and Vegetation Richness. While the results of this experiment show that less variety is better for nutrient removal, other studies have suggested that more variety that exists in plant polycultures is better. Karathanasis et al. (2003) found that some polyculture species form vegetation patterns that have enhanced ecological and functional values, while other vegetative species may be more efficient in plant communities with little to no species variety. In a study of treatment wetlands in Ohio, Picard et al. (2005) found that the growing season of some wetland plants are longer than other species. Based on these findings, Picard et al. (2005) concluded that the usage of polycultures maximizes nutrient removal.

5.4.3 Nutrient Removal and Vegetation Composition. Studies have shown that community types (i.e., submerged, floating, etc.) have significant effects on nutrient removal; however, the species that comprise the communities do not have an obvious effect (Kadlec 2005). Determining whether a particular community had an overwhelming effect on nutrient removal in the present study is difficult because each wetland cell had the same vegetation communities, and for the most part, the communities contained the same species.

5.4.4 Nutrient Removal and Vegetation Dominance. The performance of vegetation that comprised the plant community in WC2 was possibly due to the most dominant species present: duckweed, crowfoot sedge and spiderlily. Out of the three species, duckweed had the most extensive cover. These findings are somewhat different than what would be expected according to some past studies. For instance, Wolverton (1987) found that a continuous mat of duckweed cover can reduce the exchange of O_2 between the atmosphere and water, thus prohibiting microbial interactions that are important to nutrient removal. WC2 would be expected to have the lowest nutrient removal efficiency if Wolverton's (1987) findings were applied to this study. When comparing microcosms with and without duckweed, Picard et al. (2005) discovered that nutrient removal rates were similar and, therefore, attributed the majority of the removal to microbial processes. Again, applying these findings to the present study is problematic. With WC2 having the greatest amount of duckweed cover and the highest nutrient removal efficiency, it is difficult to attribute microbial processes as the cell's major nutrient removal pathway.

In another work, Zimmo et al. (2004) found that algae-based ponds outperformed duckweed-based ponds in nitrogen removal. Interestingly, WCs 3 and 4 both had high percentages of duckweed, but had even higher amounts of algae. In fact, WC4 had the greatest amount of algae out of the four wetland cells, but still had the lowest removal efficiency for TSS, TP and TN.

5.5 N:P Ratios

Richardson et al. (1999) reviewed past studies and found that a balanced carbon:nitrogen:phosphorus (C:N:P) ratio is essential to sustain ecosystem productivity. Since there was no information on C for the field-scale wetlands, only the N:P ratios were analyzed. Redfield (1958) established a standard N:P ratio used for assessing the optimal amount of N and P for aquatic vegetation growth. This ratio, known as the

Redfield ratio, is 16-mol N : 1-mol P (Fourqurean and Zieman 1992). Variations of the Redfield ratio indicate that P is limiting at a N:P ratio greater than 10:1 (based on molar concentrations), while N is limiting at a ratio less than 5:1 (based on molar concentrations) (Toetz 1990). Based on either the Redfield ratio or deviations of this ratio, N is a limiting nutrient in the field-scale wetlands.

5.6 Moist-Soil Management

Average river concentrations for TSS, TP and TN during the two start-up periods tended to guide the direction of the parameter concentrations in the field-scale wetlands. For instance, the river concentrations of TSS in June 2003 were higher than the September/October 2004 concentrations, at 295.93-mgL^{-1} and 256.53-mgL^{-1}, respectively. For TP and TN, the river concentrations in September/October 2004 were higher than the June 2003 concentrations.

Lower TSS levels in the start-up period after moist-soil management began could possibly be attributed to vegetation. Ideally, the wetland system should mature and the vegetation should become more established during the first year of operation. The more vegetation there is, the more TSS retention that is possible, and thus, the lower the TSS concentrations (Kadlec and Knight 1996, Braskerud 2001). This, however, does little to explain why TSS removal was lower in September/October 2004. The fact that more vegetation was present should lead to more TSS retention. Since this was not the case, it might be safe to assume that other processes were in effect and that retention by vegetation was not the primary removal pathway of TSS.

Removal efficiencies for TP and TN greatly increased after the moist-soil management began. This could be attributed to the wetland processes becoming more established during the time of the second start-up period. The percent reductions during June 2003 could be lower simply because the removal efficiencies represented the initial start-up conditions.

5.7 Pilot-Scale versus Field-Scale Wetland Systems

Similar nutrient removal efficiencies could be attributed to similar [TSS], [TP] and [TN] in the Trinity River. For instance, the average river concentrations for the three parameters during the eight-yr pilot study were 245-mgL^{-1} TSS, 5.39-mgL^{-1} TN and 0.98-mgL^{-1} TP. For the field-scale study, the average river levels were 225-mgL^{-1} TSS, 3.14-mgL^{-1} TN and 0.85-mgL^{-1} TP. While removal efficiency of TSS was almost the same for the two systems, the pilot-scale wetlands removed TN and TP more efficiently. Reduction percentages of TN and TP were possibly higher for the pilot-scale system because the average river concentration of these parameters was higher than it was for the field-scale study.

Higher TP and TN removal in the pilot scale system for train 2 may be the result of several individual factors or a combination of the factors. Similar to the average depths for the field-scale wetlands (0.32-m), the average depth for the wetland cells in train 2 was approximately 0.30-m. The average depth for the other two trains in the pilot-scale system was approximately 0.46-m. The shallower depth may have contributed to better removal of TN and TP.

Along with depth, the wetland cells in the pilot study were considerably smaller than the field-scale wetlands. The pilot-scale wetlands were all similar in size; therefore, size was not an issue as to why train 2 outperformed the other two trains. When assessing the differences between the pilot-scale and field-scale studies, wetland size could be a major factor contributing to the difference in TN and TP removal among the two systems.

Another possible factor that might have an impact on the removal efficiency of TP and TN is vegetation. As mentioned in an earlier section of this paper, the individual wetland cells in the pilot-scale system typically consisted of different vegetative compositions. The exception to this would be train 3, where the wetland cells in this train had no selective planting. The species that were specific to the wetland cells in train 2 included: pondweed (*Potamogeton nodosus*), duckweed (*Lemna* spp.), soft rush

(*Juncus effusus*), water primrose (*Ludwigia peploides*), softstem bulrush (*Scirpus validus*), cattail (*Typha* sp.), smartweed (*Polygonum hydropiperoides*) and grassy arrowhead (*Sagittaria graminea*). All of these species were in the list of recommended plants for the field-scale wetlands (Appendix B, Table B-2), with the exception of cattail. Out of the vegetation species present in train 2 of the pilot-scale study, only three species occurred in WC2 of the field-scale wetlands: duckweed, grassy arrowhead and water primrose. These species, along with softstem bulrush and smartweed, were present in the other three field-scale wetland cells.

While the first two cells in train 2 consisted of specific plants, the last cell was comprised of a mixture of all of the species found in the wetland cells from trains 1 and 2. This mixed culture of plants could have encouraged greater TN and TP removal. On the other hand, it is possible that train 2 was more efficient in nutrient removal because of the concentrated species located in wetland cells 4 (soft rush and duckweed) and 5 (pondweed, water primrose and duckweed).

All of the factors taken together or different combinations of these factors may explain why the pilot-scale wetlands were more efficient in TN and TP removal. It is also possible that these factors didn't play any role in the pilot-scale wetlands outperforming the field-scale wetlands, and that operation time was the main reason for the difference in TN and TP removal. While both systems had periods of down time (approximately 31-mos for the pilot study and 4-mos for the field-scale study), the pilot-scale wetlands were operated at a much greater length than the present field-scale study. According to past studies, the field-scale wetlands may not be old enough to be considered as fully operational for some processes (i.e., nitrification) (Craft 1997, International Water Association 2000). Hence, wetland age may be included in the list of factors that are possibly contributing to the difference in nutrient removal efficiency among the pilot-scale and field-scale wetlands.

VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Tarrant Regional Water District's field-scale wetlands were monitored to determine the removal efficiency of TSS, TP and TN. Water quality and vegetation data from the first two years of operation were used in cell-to-cell and system-wide nutrient removal analyses. Temporal and spatial analyses were conducted to determine the efficiency on a monthly, seasonal and yearly basis, along with acknowledge removal efficiency within the wetland system. This would aid in recognizing which cell was most effective in nutrient removal, as well as would assess the effectiveness of the system as a whole. The results of this study were then used in a comparison analysis with the results from the pilot-scale operation. This would allow the identification of areas of improvement that could be implemented into the current operation of the field-scale wetlands.

Temporal analyses of TSS, TP and TN displayed varying monthly trends. For each parameter, average concentrations regularly increased or decreased throughout the two years of operation; however, the concentrations generally fell into a range of values. Monthly TSS averages for September 2004 and March 2005 fell outside of the general range of TSS values. Two months, January and February 2005, were lower than the range given for TP, while three months (October 2003, February and September 2004) were outside of the TN range of values.

Seasonal and yearly [TSS], [TP] and [TN] also displayed temporal trends. TSS levels generally increased as the seasons progressed in order. Average [TP] were approximately the same throughout the seasons, with the exception of a significant drop in value during the Winter 2004 season. Similarly, the average TN value for the Winter 2004 season dropped considerably from what would be considered a slightly increasing trend for TN among the consecutive seasons. Yearly TSS and TN levels increased in the second year of operation, while yearly [TP] decreased during year 2.

Average river concentrations of TSS, TP and TN appeared to have a direct effect in all of the temporal analyses. Months that were higher or lower than the given ranges for TSS, TP and TN tended to have higher or lower river concentrations of the parameters. Likewise, variations in seasonal and yearly average [TSS], [TP] and [TN] seemed to mirror the seasonal and yearly river concentrations.

Vegetation and precipitation also seemed to contribute to the variations in nutrient concentrations.

Spatial trends of TSS, TP and TN were typically the same for the monthly, seasonal and yearly analyses. The average concentrations were higher in the beginning of the wetland system than at the end of the system. For each parameter, average values decreased moving site-to-site in the field-scale system.

For the correlation analysis, the strongest correlations existed between similar parameters (i.e., TSS and TVSS, TP and OK, ALK and HARD). The strongest correlation among the water quality parameters, not including the like parameters, was between TSS and turbidity.

The results of the percent reduction analysis indicated that WC2 was the most efficient cell in TSS, TP and TN removal, while WC4 had the lowest removal efficiency of the three parameters. The field-scale wetlands (PS to WC4) had high overall removal efficiency of TSS, TP and TN, with reductions at 97%, 47% and 68%, respectively.

The vegetation analysis resulted in WCs 1 and 3 having the greatest vegetative species richness, while WC2 had the least amount of species richness. Vegetation composition did not appear to have a great impact on wetland cell performance in that the four wetland cells all had the same types of plants (submerged, floating, emergent and terrestrial). The dominance of one or two species could have been the result of better nutrient removal for WC2. This cell was dominated by duckweed (*Lemna* spp.), crowfoot sedge (*Carex crus-corvi*) and spiderlily (*Hymenocallis liriosme*).

The majority of the N:P ratios calculated for each site within the field-scale wetland system indicate that N is a limiting factor.

The moist-soil management analysis displayed that the start-up period following the summer draw down had better removal efficiencies for TP and TN. TSS removal was better for the initial start-up period of the field-scale operation.

The comparison analysis between the pilot-scale and field-scale wetlands proved that the removal efficiency of TSS was similar. The pilot-scale system had better TP and TN removal. Without conducting further research, it is hard to determine why the pilot-scale wetlands outperformed the field-scale wetlands. It may be a result of size differences, age, and/or vegetation composition and richness.

The findings of this study suggest that during the first two years of operation, the field-scale wetlands' performance was comparable to the pilot-scale wetlands which were operated for eight years.

6.2 Conclusions

The temporal and spatial results of this study did not yield any significant results; therefore, there were no major conclusions to report. Likewise, the removal efficiency data did not produce any extraordinary results.

Moist-soil management offered some interesting data on nutrient removal efficiencies; however, due to the limited amount of data prior to and following the draw down strategy, no significant findings were reported in this study.

With the amount of data that exists for the field-scale wetlands, a fair comparison among the pilot-scale and field-scale systems cannot be made at this time.

Of most significance, the N:P ratio analysis produced the biggest conclusion from this study. Due to the significant limitation in N throughout the field-scale system, it is strongly suggested to supplement the wetland system with artificial N. Going further, the N appeared to be more limited as it moved consecutively throughout the system, implying that the amount of added artificial N should increase as the wetland sites progress. Supplementing the field-scale wetlands with artificial N will increase other wetland activities, such as P retention.

6.3 Recommendations

As a result of the study, the following recommendations for further research on the current and future operations of the field-scale wetlands are made:

- To determine which wetland cell in the field-scale system is the most efficient, water needs to be diverted and passed through each individual cell. In other words, once water has been passed through the sedimentation basin, it needs to get diverted to a particular wetland cell. For instance, to determine the true efficiency of WC2, water should be diverted from entering WC1 and directed into WC2. Once the water has flowed through WC2, divert the water again from passing through WCs 3 and 4. The nutrient removal efficiency would only reflect WC2's capabilities and not have to take into consideration the removal that has already occurred in WC1.
- To get an indication of how the wetlands are functioning, invertebrate populations should be sampled. Mitsch and Gosselink (2000) consider invertebrates as the link between plants and their detritus, as well as between plants and animals. Invertebrates often represent different successional and functional stages of the wetlands. For instance, dragonflies and damselflies are present around wetlands with good water quality. Invertebrate sampling should be conducted at least once every year.
- Soil sampling should occur more than once a year. Similar to invertebrates, the sediment can tell how each wetland cell is performing on a functional basis. Rather than just focusing on the accumulation of nutrients, metals and other toxins (which is currently done), the soil sampling should investigate redox potential, pH and a number of processes including carbon, nitrogen and phosphorus transformations. The health of the soil is a good indication of the health of the vegetation, and thus the health of the wetland. Hemond and Benoit (1988) point out that soils best reflect the wetland's history. Soil sampling

should occur once every season, and samples should be taken at various locations within each wetland cell (including the deep zone areas).

- Plant litter should also be collected on a seasonal basis. Litter accumulation represents how fast the wetland cell/system is breaking down dead plant material.
- Seasonal analyses should also include sampling plant biomass. Random sampling should take place (rather than relying just on the established transect lines) throughout each wetland cell to get a more representative idea of what plants are dominating the wetland cell.
- Nutrient uptake through plants should also be analyzed to determine the removal efficiency of the plants that are present in each wetland cell. Samples should be sent into a lab that specializes in analyzing vegetative data. This, too, should occur on a seasonal basis to account for the various species that are present throughout the year. This will aid in recognizing which plant species perform the best at removing nutrients. Knowledge of this type of information allows for proper vegetation management to take place, such as promoting the growth and dominance of one species over another, etc.
- To get a better idea of the detention time of each cell within the wetland system, a tracer study needs to be conducted. This will not only allow the retention time to be established, it will also provide information on flow patterns. Understanding flow patterns allows for the identification of ineffective areas within each wetland cell.

The following are recommendations that primarily address moist-soil management:

- To determine how effective moist-soil management is on water quality, a study may be conducted on wetland cells participating in a moist-soil regime versus cells not implementing water draw downs.

- For a better idea of how the moist-soil management is affecting water quality and after the next series of wetland cells has been constructed and is functioning, the field-scale wetland system could be allowed to be the experimental system that allows moist-soil regimes. In the experimental cells, draw down the water during the summer every year for a minimum of three years, and then start drawing down the water every other year. This will allow enough information to determine what, if any, impact the draw downs have on water quality improvement.
- Monitor and sample vegetation before, during and after draw downs to determine what type of vegetation is present and compare these results to the cells not using the moist-soil management. This will aid in a better understanding of vegetation succession in the wetlands, as well as the performance of the vegetation species that are a result of moist-soil management and those that are not.
- Monitor the effects of fluctuating water levels (resulting from draw downs) on invertebrates and bird use.

LITERATURE CITED

Anderson, D. C., J. J. Sartoris, J. S. Thullen, and P. G. Reusch. 2003. The effects of bird use on nutrient removal in a constructed wastewater-treatment wetland. Wetlands 23:423-435.

Andersson, J. L., S. L. Bastviken, and K. S. Tonderski. 2005. Free water surface wetlands for wastewater treatment in Sweden: nitrogen and phosphorus removal. Water Science and Technology 51:39-46.

APAI (Alan Plummer Associates, Inc). 2002. Pilot-scale constructed wetlands demonstration project summary report 1993-2000: final report. Final report to the Tarrant Regional Water District, Fort Worth, TX, USA.

APAI. 2003. Vegetation survey at field-scale wetland conducted August 27, 2003. Unpublished report to the Tarrant Regional Water District, Fort Worth, TX, USA.

APHA (American Public Health Association). 1989. Standard methods for the examination of water and wastewater. American Public Health Association, Washington, DC, USA.

Best, G. R. 1987. Natural wetlands – southern environment: wastewater to wetlands, where do we go from here? p. 99-120. *In* K. R. Reddy and W. H. Smith (eds.) Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing Inc., Orlando, FL, USA.

Brix, H. 1994. Constructed wetlands for municipal wastewater treatment in Europe. p. 325-333. *In* W. J. Mitsch (ed.) Global wetlands: old world and new. Elsevier, Amsterdam, NL.

Braskerud, B. C. 2001. The influence of vegetation on sedimentation and resuspension of soil particles in small constructed wetlands. Journal of Environmental Quality 30:1447-1457.

Browning, K. and M. Greenway. 2003. Nutrient removal and plant biomass in a subsurface flow constructed wetland in Brisbane, Australia. Water Science and Technology 48:183-189.

Brueske, C. C. and G. W. Barrett. 1994. Effects of vegetation and hydrologic load on sedimentation patterns in experimental wetland ecosystems. Ecological Engineering 3:429-447.

Cameron, K.A. 2001. The efficiency and mechanisms for pollutant removal in biological wastewater treatment systems. M. S. Thesis. McGill University, Montreal, QC, CA.

Cameron, K., C. Madramootoo, A. Crolla, and C. Kinsley. 2003. Pollutant removal from municipal sewage lagoon effluents with a free-surface wetland. Water Research 37:2803-2812.

Cole, G. A. 1994. Textbook of Limnology, fourth edition. Waveland Press, Inc., Prospect Heights, IL, USA.

Conner, R. and L. James. 1996. Environment and natural resources: trends and implications. Publication prepared for the Texas Agricultural and Natural Resources Summit on Environmental and Natural Resource Policy for the 21st Century, 14 – 15 November, Kerrville, TX, USA.

Craft, C. B. 1997. Dynamics of nitrogen and phosphorus retention during wetland ecosystem succession. Wetlands Ecology and Management 4:177-187.

Day, J. W., J. Ko, J. Rybczyk, D. Sabins, R. Bean, G. Berthelot, C. Brantley, L. Cardoch, W. Conner, J. N. Day, A. J. Englande, S. Feagley, E. Hyfield, R. Lane, J. Lindsey, J. Mistich, E. Reyes, and R. Twilley. 2004. The use of wetlands in the Mississippi Delta for wastewater assimilation: a review. Ocean & Coastal Management 47:671-691.

DeBusk, T. A., L. D. Williams, and J. H. Ryther. 1983. Removal of nitrogen and phosphorus from wastewater in a water hyacinth-based treatment system. Journal of Environmental Quality 12:257-262.

Dodds, W. K. and M. R. Whiles. 2004. Quality and quantity of suspended particles in rivers: continent-scale patterns in the United States. Environmental Management 33:355-367.

Dunbabin, J. S. and K. H. Bowmer. 1992. Potential use of constructed wetlands for treatment of industrial wastewaters containing metals. The Science of the Total Environment 111:151-168.

Fennessy, M. S., C. C. Brueske, and W. J. Mitsch. 1994. Sediment deposition patterns in restored freshwater wetlands using sediment traps. Ecological Engineering 3:409-428.

Fourqurean, J. W. and J. C. Zieman. 1992. Phosphorus limitation of primary production in Florida Bay: evidence from C:N:P ratios of the dominant seagrass *Thalassia testudinum*. Limnology and Oceanography 37:162-171.

Fraser, L. H., S. M. Carty, and D. Steer. 2004. A test of four plant species to reduce total nitrogen and total phosphorus from soil leachate in subsurface wetland microcosms. Bioresource Technology 94:185-192.

Gray, P. N. and E. G. Bolen. 1987. Seed reserves in the tailwater pits of playa lakes in relation to waterfowl management. Wetlands 7:11-23.

Greenway, M. 2005. The role of constructed wetlands in secondary effluent treatment and water reuse in subtropical and arid Australia. Ecological Engineering 25:501-509.

Hach Methods. 1995. Hach Water Analysis Handbook. http://www.hach.com. Accessed: April 2006.

Haukos, D. A. and L. M. Smith. 1993. Moist-soil management of playa lakes for migrating and wintering ducks. Wildlife Society Bulletin 21:288-298.

Hemond, H. F. and J. Benoit. 1988. Cumulative impacts on water quality functions of wetlands. Environmental Management 12:639-653.

Hillman, W. S. and D. D. Culley, Jr. 1978. The uses of duckweed. American Scientist 66:442-451.

Hunter, R. G., D. L. Combs, and D. B. George. 2001. Nitrogen, phosphorus, and organic carbon removal in simulated wetland treatment systems. Archives of Environmental Contamination and Toxicology 41:274-281.

International Water Association. 2000. Constructed wetlands for pollution control: processes, performance, design and operation. IWA Publishing, London, UK.

Jing, S., Y. Lin, D. Lee, and T. Wang. 2001. Nutrient removal from polluted river water by using constructed wetlands. Bioresource Technology 76:131-135.

Johnston, C. A. 1991. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. Critical Reviews in Environmental Control 21:491-565.

Kadlec, R.H. 1994. Wetlands for wastewater polishing: free water surface wetlands. p. 335-349. *In* W. J. Mitsch (ed.) Global wetlands: old world and new. Elsevier, Amsterdam, NL.

Kadlec, R.H. 1995. Overview: surface flow constructed wetlands. Water Science and Technology 32:1-12.

Kadlec, R. H. 2005. Phosphorus removal in emergent free surface wetlands. Journal of Environmental Science and Health 40:1293-1306.

Kadlec, R. H. and J. A. Kadlec. 1979. Wetlands and water quality. p. 436-456. *In* P. E. Greeson, J. R. Clark, and J. E. Clark (eds.) Wetland Functions and Values: The State of Our Understanding. American Water Resources Association, Minneapolis, MN, USA.

Kadlec, R. H. and R. L. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL, USA.

Kadlec, R. H. and K. R. Reddy. 2001. Temperature effects in treatment wetlands. Water Environment Research 73:543-557.

Karathanasis, A. D., C. L. Potter, and M. S. Coyne. 2003. Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. Ecological Engineering 20:157-169.

Lin, Y., S. Jing, D. Lee, and T. Wang. 2002. Nutrient removal from aquaculture wastewater using a constructed wetlands system. Aquaculture 209:169-184.

Mann, R. A. 1990. Phosphorus removal by constructed wetlands: substratum adsorption. p. 97-105. *In* P. F. Cooper and B. C. Findlater (eds.) Constructed wetlands in water pollution: advances in water pollution control. Pergamon Press, Oxford, UK.

McCarey, A. E. D., B. C. Anderson, and D. Martin. 2004. Monitoring spatial and temporal variations of phosphorus within a cold climate subsurface flow constructed wetland. Journal of Environmental Engineering Science 3:51-60.

Mitchell, D. S., A. J. Chick, and G. W. Raisin. 1995. The use of wetlands for water pollution control in Australia: an ecological perspective. Water Science and Technology 32:365-373.

Mitsch, W. J. and J. G. Gosselink. 2000. Wetlands, third edition. John Wiley & Sons, New York, NY, USA.

Murphy, S. 2005. City of Boulder/USGS Water Quality Monitoring: General Information on Alkalinity. http://bcn.boulder.co.us/basin/data/NUTRIENTS/info/Alk.html. Accessed: April 2006.

Nairn, R. W. and W. J. Mitsch. 2000. Phosphorus removal in created wetland ponds receiving river overflow. Ecological Engineering 14:107-126.

NWF (National Wildlife Federation). 2005. Water Planning – Region C. National Wildlife Federation, Environmental Defense, and Lone Star Chapter of the Sierra Club collaborative project. http://www.texaswatermatters.org/region_c.htm. Accessed: January 2005.

Nokes, R. L., C. P. Gerba, and M. M. Karpiscak. 2003. Microbial water quality improvement by small scale on-site subsurface wetland treatment. Journal of Environmental Science and Health, Part A – Toxic/Hazardous Substances & Environmental Engineering A38:1849-1855.

Picard, C. R., L. H. Fraser, and D. Steer. 2005. The interacting effects of temperature and plant community type on nutrient removal in wetland microcosms. Bioresource Technology 96:1039-1047.

Ran, N., M. Agami, and G. Oron. 2004. A pilot study of constructed wetlands using duckweed (*Lemna gibba* L.) for treatment of domestic primary effluent in Israel. Water Research 38:2241-2248.

Redfield, A. C. 1958. The biological control of chemical factors in the environment. American Scientist 46:561-600.

Reddy, K. R. and W. F. DeBusk. 1987. Nutrient storage capabilities of aquatic and wetland plants. p. 337-357. *In* K. R. Reddy and W. H. Smith (eds.) Aquatic plants for wetland treatment and resource recovery. Magnolia Publishing Inc., Orlando, FL, USA.

Reed, S. C., R. W. Crites, and E. J. Middlebrooks. 1995. Natural Systems for Water Management and Treatment. McGraw-Hill, New York, NY, USA.

Region C Water Plan. 2001. Senate Bill1, Region C Water Plan. http://www.regionc water.org/Planning/Waterplan/index.cfm. Accessed: January 2005.

Richardson, C. J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. Science 228:1424-1427.

Richardson, C. J., G. M. Ferrell, and P. Vaithiyanathan. 1999. Nutrient effects on stand structure, resorption efficiency, and secondary compounds in Everglades sawgrass. Ecology 80:2182-2192.

Saunders, D. L. and J. Kalff. 2001. Nitrogen retention in wetlands, lakes and rivers. Hydrobiologia 443:205-212.

Spieles, D. J. and W. J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: a comparison of low- and high-nutrient riverine systems. Ecological Engineering 14:77-91.

Steer, D. N., L. H. Fraser, J. Boddy, and B. A. Seibert. 2002. Efficiency of small constructed wetlands for subsurface treatment of single-family domestic effluent. Ecological Engineering 18:429-440.

Steer, D. N., L. H. Fraser, and B. A. Seibert. 2005. Cell-to-cell pollution reduction effectiveness of subsurface domestic treatment wetlands. Bioresource Technology 96:969-976.

Straškraba, M. 1996. Ecotechnological methods for managing non-point source pollution in watersheds, lakes and reservoirs. Water Science and Technology 33:73-80.

Toet, S., R. S. P. Van Logtestijn, M. Schreijer, R. Kampf, and J. T. A. Verhoeven. 2005. The functioning of a wetland system used for polishing effluent from a sewage treatment plant. Ecological Engineering 25:101-124.

Toetz, D. 1990. Agricultural impacts on stream water quality. Environmental Institute, Oklahoma State University, Stillwater, OK, USA. Publication No. A-113.

TPWD (Texas Parks and Wildlife Department). 2006. Richland Creek WMA. http://www.tpwd.state.tx.us/wma/find_a_wma/. Accessed: February 2006.

TRWD (Tarrant Regional Water District). 2002. Richland-Chambers Wetlands Water Reuse Project: Integrated Water Supply and Wildlife Habitat Project. Tarrant Regional Water District, Fort Worth, TX, USA.

TWDB (Texas Water Development Board). 2002. Water for Texas – 2002. http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2002/FinalWaterPlan2002.asp. Accessed: January 2005.

Vymazal, J. 2002. The use of subsurface constructed wetlands for wastewater treatment in the Czech Republic: 10 years experience. Ecological Engineering 18:633-646.

Wolverton, B. C. 1987. Aquatic plants for wastewater treatment: an overview. p. 3-15. *In* K. R. Reddy and W. H. Smith (eds.) Aquatic plants for water treatment and resource recovery. Magnolia Publishing Inc., Orlando, FL, USA.

Zimmo, O. R., N. P. van der Steen, and H. J. Gijzen. 2004. Nitrogen mass balance across pilot-scale algae and duckweed-based wastewater stablisation ponds. Water Research 38:913-920.

APPENDIX A

FLOW BALANCE AND MASS BALANCE EQUATIONS FOR THE PILOT-SCALE WETLAND SYSTEM

Flow Balance Equation

The flow balance model (Equation A-1), developed by Alan Plummer Associates, Inc. (APAI), is as follows:

Average Inflow – Average Outflow + Precipitation – Calculated Evapotranspiration ± Change in Volume = Volume Estimation Variance (A-1)

Water quality and flow sampling station were located at the weirs for each wetland cell and settling pond as indicated in Figure 2.1. APAI developed calibration curves for each weir based on timed direct volumetric flow measurements using a bucket and stopwatch (APAI 2002). APAI used these calibration curves to determine flow from the physical measurements taken at each weir (APAI 2002). New calibration curves were generated following any weir structure modifications (APAI 2002).

Mass Balance Equation

Mass balances for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) were calculated on a weekly basis except when breaks in system operation or other factors resulted in gaps of greater time periods in the data (APAI 2002). The mass balance equation used by APAI is as follows in Equation A-2:

Initial Mass + Mass In = Final Mass + Mass Out + Mass Removed (A-2)

APAI used measured flows and constituent concentrations to estimate incoming, outgoing and stored mass in each wetland cell and settling pond (APAI 2002). Flow-weighted averages of the concentrations and the corresponding average flow were used to develop the mass in and mass out values (APAI 2002). Finally, APAI calculated the percent removal of the constituent as the mass removed within a period of time divided by the mass in the inflow over the same period of time (APAI 2002).

APPENDIX B

VEGETATION SPECIES FOR THE PILOT-SCALE WETLAND SYSTEM

Table B-1. Vegetation species found in the pilot-scale wetland system during the entire operational period, 1993 through 2000.

Common Name	Scientific Name	Author
Algal Mat		
Alligator Weed	*Alternanthera philoxeroides*	(Mart.) Griseb.
American Water Willow	*Justicia americana*	(L.) Vahl
Annual Sumpweed	*Iva annua*	L.
Aster	*Asteraceae family*	
Balloon Vine	*Cardiospermum halicacabum*	L.
Beak Rush	*Rynchospora macrostaycha*	Torr.
Bermuda Grass	*Cynodon dactylon*	L.
Black Willow	*Salix nigra*	Marsh.
Camphor Weed	*Pluchea camphorata*	(L.) DC.
Caric Sedge	*Carex sp.*	
Cattail	*Typha latifolia*	L.
Climbing Hempweed	*Mikanea scandens*	(L.) Willd.
Cocklebur	*Xanthium strumarium*	L.
Colorado River-Hemp	*Sesbania herbacea*	Muhl.
Coontail	*Ceratophylum demersum*	L.
Crab Grass	*Digitaria sp.*	
Crowfoot Sedge	*Carex crus-corvi*	Shuttlw. ex Kuntze
Duckweed	*Lemna spp.*	
Eryngo	*Eryngium leavenworthii*	T. & G.
Fescue Grass	*Vulpia octoflora*	(Walt.) Rydb.
Flatsedge	*Cyperus sp.*	
Frog Fruit	*Lippia lanceolata*	Michx.
Grassy Arrowhead	*Sagittaria graminea*	Michx.
Horned Pondweed	*Zannichellia palustris*	L.
Illinois Bundle Flower	*Desmanthus illinoensis*	(Michx.) MacM.
Jungle Rice	*Echinochloa colonum*	(L.) Link
Knotroot Bristlegrass	*Setaria geniculata*	(Lam.) Beauv.
Maiden Cane	*Panicum hemitomon*	Schult.
Morning Glory	*Ipomoea sp.*	
Mosquito Fern	*Azolla caroliniana*	Willd.
Nitella Algea	*Nitella sp.*	
Nut Sedge	*Cyperus rotundus*	L.
Open Water		
Other/Unknown		
Panic Grass	*Panicum sp.*	
Parrotfeather	*Myriophyllum brasiliense*	Camb.
Partridge Pea	*Chamaecrista fasciculata*	(Michx.) Greene

Table B-1. Continued.

Common Name	Scientific Name	Author
Paspalum	*Paspalum sp.*	
Pondweed	*Potamogeton nodosus*	Poir.
Ragweed	*Ambrosia artemisiifolia*	L.
Rice-Cut Grass	*Leersia oryzoides*	(L.) Sw.
Smartweed	*Polygonum hydropiperoides*	Michx.
Softstem Bulrush	*Scirpus validus*	Vahl
Sorghum bicolor	*Sorghum bicolor*	(L.) Moench
Southern Naiad	*Najas guadalupensis*	(Spreng.) Magnus
Squarestem Spikerush	*Eleocharis quadrangulata*	(Michx.) R. & S.
Star Grass	*Heteranthera dubia*	(Jacq.) MacM.
Texas Rush	*Juncus texanus*	(Engelmann) Coville in J. K. Small
Toothcup	*Ammannia coccinea*	Rottb.
Water Celery	*Vallisneria americana*	Michx.
Water Clover	*Marsilea vestita ssp. vestita*	Hook & Grev.
Water Primrose	*Ludwigia peploides*	HBK.
Willow Primrose	*Ludwigia decurrens*	Walt.

Table B-2. Recommended plant species from the pilot-scale testing.

Wetland Zone	Common Name	Scientific Name
Very Shallow Marsh	Crowfoot Sedge	*Carex crus-corvi*
	Squarestem Spikerush	*Eleocharis quadrangulata*
	Spikerush	*Eleocharis spp.*
	Soft Rush	*Juncus effusus*
	Jungle Rice	*Echinochloa colona*
Shallow Marsh	Grassy Arrowhead	*Sagittaria graminea*
	Softstem Bulrush	*Scirpus validus*
	Squarestem Spikerush	*Eleocharis quadrangulata*
	Smartweed	*Polygonum hydropiperoides*
	Water Stargrass	*Heteranthera dubia*
	Water Celery	*Vallisneria americana*
	Coontail	*Ceratophyllum demersum*
	Crowfoot Sedge	*Carex crus-corvi*
Deep Marsh	Softstem Bulrush	*Scirpus validus*
	Grassy Arrowhead	*Sagittaria graminea*
	Squarestem Spikerush	*Eleocharis quadrangulata*
	Water Stargrass	*Heteranthera dubia*
	Water Celery	*Vallisneria americana*
	Coontail	*Ceratophyllum dermersum*
	Duckweed	*Lemna spp.*

Table B-2. Continued.

Wetland Zone	Common Name	Scientific Name
Deep Water Zones	Pondweed	*Potamogeton nodosus*
	Coontail	*Ceratophyllum demersum*
	Water Stargrass	*Heteranthera dubia*
	Water Celery	*Vallisneria americana*
	Duckweed	*Lemna spp.*

APPENDIX C

MONTHLY, SEASONAL AND YEARLY AVERAGE CONCENTRATIONS

Table C-1. Monthly average concentrations for each individual site in the field-scale wetland system. The standard deviation follows the "±" sign, and the sample size is in the parentheses.

Parameter	PS	SB	WC1
TSS (mgL^{-1})	238.04 ± 181.11 (66)	72.85 ± 35.86 (65)	47.60 ± 37.80 (62)
TVSS (mgL^{-1})	21.29 ± 14.85 (63)	9.59 ± 5.47 (64)	8.41 ± 5.63 (61)
TP (mgL^{-1})	0.85 ± 0.30 (67)	0.76 ± 0.29 (66)	0.68 ± 0.27 (63)
OP (mgL^{-1})	0.77 ± 0.37 (67)	0.73 ± 0.34 (66)	0.63 ± 0.30 (63)
NOX (mgL^{-1})	2.50 ± 2.38 (66)	2.41 ± 2.20 (65)	1.49 ± 1.42 (62)
NH3 (mgL^{-1})	0.08 ± 0.06 (66)	0.10 ± 0.13 (65)	0.10 ± 0.15 (62)
TKN (mgL^{-1})	0.68 ± 0.35 (66)	0.59 ± 0.24 (65)	0.67 ± 0.31 (62)
TN (mgL^{-1})	3.14 ± 2.42 (66)	2.97 ± 2.20 (65)	2.13 ± 1.46 (62)
ALK (mgL^{-1})	111.57 ± 25.95 (62)		
HARD (mgL^{-1})	166.39 ± 24.80 (64)		
CHLOR (mgL^{-1})	51.53 ± 20.45 (65)	51.64 ± 20.39 (63)	50.81 ± 19.59 (60)
TURB (ntu)	242.57 ± 201.02 (60)	93.25 ± 61.84 (59)	57.70 ± 46.41 (56)
TEMP (° C)	21.56 ± 7.21 (111)	21.49 ± 7.29 (112)	20.97 ± 7.58 (110)
pH (pH/units)	8.08 ± 0.49 (111)	8.21 ± 0.53 (112)	8.06 ± 0.75 (109)
DO (mgL^{-1})	8.27 ± 2.13 (110)	9.19 ± 2.13 (111)	8.12 ± 3.89 (108)
COND ($mScm^{-1}$)	567.38 ± 143.95 (111)	598.30 ± 113.30 (112)	588.64 ± 112.04 (109)
FLOW (m^3d^{-1})	49564.54 ± 7570.19 (115)	47642.06 ± 9983.15 (114)	46678.45 ± 8669.60 (70)

Table C-1. Continued.

Parameter	WC2	WC3	WC4	AC
TSS (mgL^{-1})	11.56 ± 15.29 (58)	7.48 ± 12.49 (64)	6.43 ± 8.49 (65)	29.15 ± 35.42 (62)
TVSS (mgL^{-1})	3.83 ± 3.33 (57)	3.00 ± 2.56 (63)	2.84 ± 2.60 (64)	4.29 ± 5.01 (61)
TP (mgL^{-1})	0.54 ± 0.24 (59)	0.46 ± 0.21 (65)	0.45 ± 0.21 (66)	0.37 ± 0.22 (64)
OP (mgL^{-1})	0.51 ± 0.24 (59)	0.44 ± 0.22 (65)	0.44 ± 0.21 (66)	0.31 ± 0.17 (64)
NOX (mgL^{-1})	0.61 ± 0.90 (58)	0.35 ± 0.63 (64)	0.33 ± 0.52 (65)	0.17 ± 0.21 (63)
NH3 (mgL^{-1})	0.19 ± 0.28 (58)	0.12 ± 0.21 (64)	0.16 ± 0.28 (65)	0.10 ± 0.12 (63)
TKN (mgL^{-1})	0.80 ± 0.46 (58)	0.69 ± 0.37 (64)	0.69 ± 0.42 (65)	0.56 ± 0.26 (63)
TN (mgL^{-1})	1.40 ± 1.04 (58)	1.04 ± 0.74 (64)	1.02 ± 0.68 (65)	0.73 ± 0.33 (63)
ALK (mgL^{-1})			128.43 ± 32.37 (60)	128.42 ± 37.65 (60)
HARD (mgL^{-1})			166.60 ± 19.42 (62)	165.37 ± 22.20 (61)
CHLOR (mgL^{-1})	49.79 ± 20.39 (56)	50.72 ± 20.38 (61)	49.98 ± 20.45 (63)	50.71 ± 22.43 (62)
TURB (ntu)	12.35 ± 14.67 (52)	6.90 ± 7.33 (58)	5.22 ± 5.44 (59)	23.70 ± 37.44 (57)
TEMP (° C)	20.25 ± 8.19 (102)	21.16 ± 7.95 (112)	21.16 ± 8.00 (113)	20.84 ± 6.96 (97)
pH (pH/units)	7.91 ± 0.74 (102)	8.29 ± 0.73 (112)	8.10 ± 0.73 (113)	7.81 ± 0.59 (97)
DO (mgL^{-1})	6.58 ± 3.91 (101)	8.38 ± 3.70 (109)	7.22 ± 3.70 (112)	7.09 ± 2.37 (96)
COND ($mScm^{-1}$)	583.34 ± 109.01 (102)	587.24 ± 109.81 (112)	590.79 ± 113.46 (112)	581.31 ± 133.04 (97)
FLOW (m^3d^{-1})	52281.52 ± 17435.48 (76)	56924.62 ± 19117.36 (76)	36495.35 ± 11193.35 (76)	42559.29 ± 26861.41 (84)

Table C-2. Average concentrations for the field-scale system's water quality parameters on a seasonal basis. The standard deviation follows the "±" sign, and the sample size is in the parentheses.

Parameter	Summer 2003	Fall 2003	Winter 2003
TSS (mgL^{-1})	52.67 ± 83.96 (83)	48.74 ± 90.20 (84)	52.53 ± 108.09 (77)
TVSS (mgL^{-1})	6.63 ± 7.32 (75)	5.66 ± 6.47 (84)	7.45 ± 9.90 (77)
TP (mgL^{-1})	0.62 ± 0.35 (84)	0.62 ± 0.24 (84)	0.64 ± 0.34 (77)
OP (mgL^{-1})	0.58 ± 0.36 (84)	0.61 ± 0.28 (84)	0.62 ± 0.34 (77)
NOX (mgL^{-1})	1.17 ± 1.43 (84)	0.80 ± 1.00 (77)	0.80 ± 1.34 (77)
NH3 (mgL^{-1})	0.068 ± 0.065 (77)	0.30 ± 0.37 (84)	0.095 ± 0.078 (77)
TKN (mgL^{-1})	0.62 ± 0.34 (77)	0.77 ± 0.44 (84)	0.80 ± 0.32 (77)
TN (mgL^{-1})	1.80 ± 1.48 (77)	1.50 ± 1.11 (84)	1.60 ± 1.35 (77)
ALK (mgL^{-1})	125.48 ± 21.21 (29)	132.22 ± 22.09 (36)	117.62 ± 14.19 (30)
HARD (mgL^{-1})	159.44 ± 18.68 (34)	155.29 ± 23.26 (33)	165.64 ± 19.78 (33)
CHLOR (mgL^{-1})	52.36 ± 25.23 (84)	56.83 ± 20.14 (76)	56.97 ± 23.78 (72)
TURB (ntu)	65.05 ± 112.00 (70)	55.89 ± 89.52 (56)	60.54 ± 133.95 (77)
TEMP (° C)	29.66 ± 2.34 (212)	21.24 ± 4.39 (91)	10.35 ± 3.13 (117)
pH (pH/units)	7.85 ± 0.41 (211)	7.66 ± 0.45 (91)	8.19 ± 0.58 (117)
DO (mgL^{-1})	6.60 ± 3.34 (209)	5.62 ± 2.45 (91)	10.54 ± 1.78 (117)
COND ($mScm^{-1}$)	612.70 ± 134.96 (211)	608.40 ± 102.64 (91)	612.24 ± 101.59 (116)
FLOW (m^3d^{-1})	51966.87 ± 22247.00 (227)	44934.09 ± 14909.15 (91)	42769.89 ± 7300.37 (115)

Table C-2. Continued.

Parameter	Spring 2004	Fall 2004	Winter 2004	Spring 2005
TSS (mgL^{-1})	70.01 ± 81.34 (56)	68.88 ± 131.70 (56)	65.48 ± 105.27 (42)	84.85 ± 160.30 (44)
TVSS (mgL^{-1})	10.61 ± 8.60 (56)	7.54 ± 9.43 (56)	7.73 ± 8.11 (42)	10.01 ± 14.69 (43)
TP (mgL^{-1})	0.63 ± 0.24 (63)	0.57 ± 0.26 (56)	0.28 ± 0.19 (42)	0.64 ± 0.28 (44)
OP (mgL^{-1})	0.54 ± 0.28 (63)	0.54 ± 0.27 (56)	0.23 ± 0.16 (42)	0.58 ± 0.28 (44)
NOX (mgL^{-1})	0.99 ± 1.47 (63)	1.89 ± 3.13 (56)	0.91 ± 0.89 (42)	1.75 ± 1.72 (44)
NH3 (mgL^{-1})	0.063 ± 0.039 (63)	0.067 ± 0.047 (56)	0.10 ± 0.092 (42)	0.075 ± 0.044 (44)
TKN (mgL^{-1})	0.71 ± 0.34 (63)	0.45 ± 0.19 (56)	0.42 ± 0.28 (42)	0.77 ± 0.24 (44)
TN (mgL^{-1})	1.70 ± 1.46 (63)	2.34 ± 3.14 (56)	1.34 ± 1.02 (42)	2.52 ± 1.83 (44)
ALK (mgL^{-1})	125.60 ± 13.29 (24)	142.49 ± 62.74 (24)	111.71 ± 8.58 (18)	93.14 ± 40.23 (21)
HARD (mgL^{-1})	183.17 ± 24.33 (24)	165.63 ± 16.44 (24)	157.18 ± 14.93 (18)	183.52 ± 17.67 (21)
CHLOR (mgL^{-1})	45.85 ± 13.49 (56)	46.52 ± 14.36 (56)	31.14 ± 7.45 (42)	57.43 ± 12.28 (44)
TURB (ntu)	56.30 ± 68.66 (56)	61.30 ± 104.61 (56)	76.73 ± 103.52 (42)	87.15 ± 180.43 (44)
TEMP (° C)	20.72 ± 4.04 (108)	21.21 ± 3.95 (95)	11.96 ± 3.29 (66)	21.88 ± 3.98 (70)
pH (pH/units)	8.64 ± 1.01 (108)	7.84 ± 0.58 (95)	8.25 ± 0.50 (66)	8.38 ± 0.54 (70)
DO (mgL^{-1})	8.44 ± 2.63 (108)	6.43 ± 2.53 (95)	9.89 ± 2.63 (59)	9.52 ± 3.70 (70)
COND ($mScm^{-1}$)	540.20 ± 109.59 (108)	553.46 ± 87.64 (95)	442.76 ± 69.40 (66)	666.41 ± 70.12 (70)
FLOW (m^3d^{-1})	46406.95 ± 10697.70 (86)	45608.48 ± 6560.47 (33)	48673.19 ± 8994.73 (21)	45386.09 ± 10370.15 (38)

Table C-3. Average concentrations for the field-scale system's water quality parameters on a yearly basis. The standard deviation follows the "±" sign, and the sample size is in the parentheses.

Parameter	Year 1	Year 2
TSS (mgL^{-1})	54.77 ± 91.84 (300)	72.82 ± 133.76 (142)
TVSS (mgL^{-1})	7.33 ± 8.26 (292)	8.35 ± 10.96 (141)
TP (mgL^{-1})	0.63 ± 0.30 (308)	0.51 ± 0.29 (142)
OP (mgL^{-1})	0.59 ± 0.32 (308)	0.46 ± 0.29 (142)
NOX (mgL^{-1})	0.94 ± 1.32 (301)	1.55 ± 2.27 (142)
NH3 (mgL^{-1})	0.14 ± 0.22 (301)	0.080 ± 0.064 (142)
TKN (mgL^{-1})	0.73 ± 0.37 (301)	0.54 ± 0.28 (142)
TN (mgL^{-1})	1.64 ± 1.34 (301)	2.10 ± 2.33 (142)
ALK (mgL^{-1})	125.56 ± 19.10 (119)	117.25 ± 49.55 (63)
HARD (mgL^{-1})	164.58 ± 23.34 (124)	169.18 ± 19.45 (63)
CHLOR (mgL^{-1})	53.42 ± 21.97 (288)	45.35 ± 15.77 (142)
TURB (ntu)	59.84 ± 106.61 (259)	73.87 ± 132.03 (142)
TEMP (° C)	22.10 ± 8.07 (528)	18.77 ± 5.73 (231)
pH (pH/units)	8.06 ± 0.71 (527)	8.12 ± 0.59 (231)
DO (mgL^{-1})	7.69 ± 3.27 (525)	8.31 ± 3.37 (224)
COND ($mScm^{-1}$)	596.97 ± 120.98 (526)	556.06 ± 115.62 (231)
FLOW (m^3d^{-1})	47348.81 ± 14287.51 (518)	44605.74 ± 7993.59 (92)

APPENDIX D

SPATIAL VARIABILITY IN TSS, TP AND TN CONCENTRATIONS – ON A MONTHLY AND SEASONAL BASIS

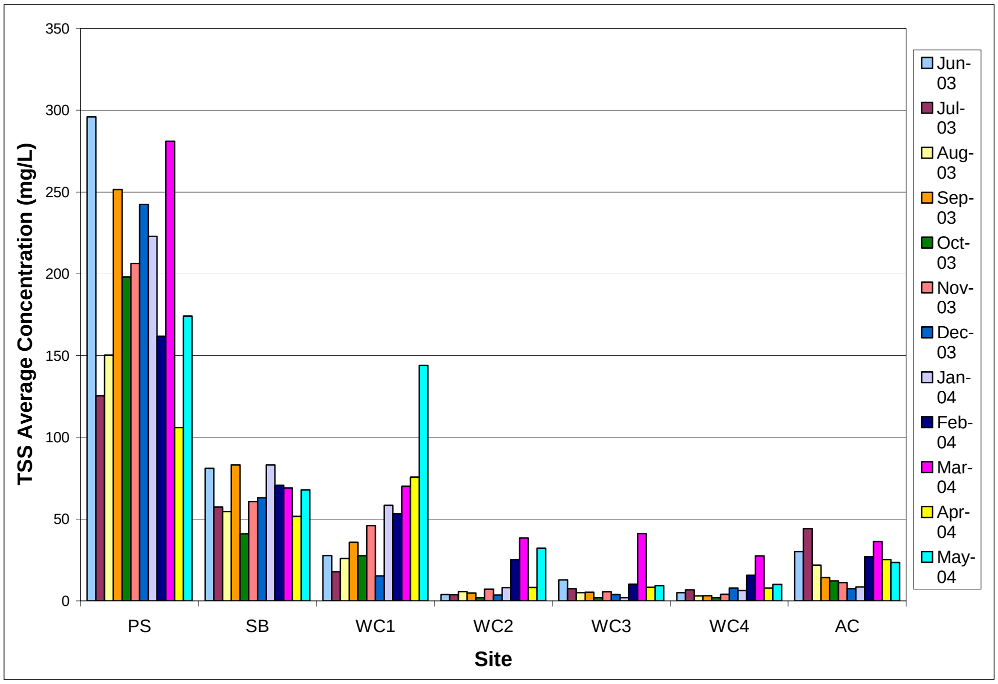

Figure D-1. Spatial variation of monthly average concentrations for TSS during the first year of operation (June 2003 – May 2004) of the field-scale wetlands.

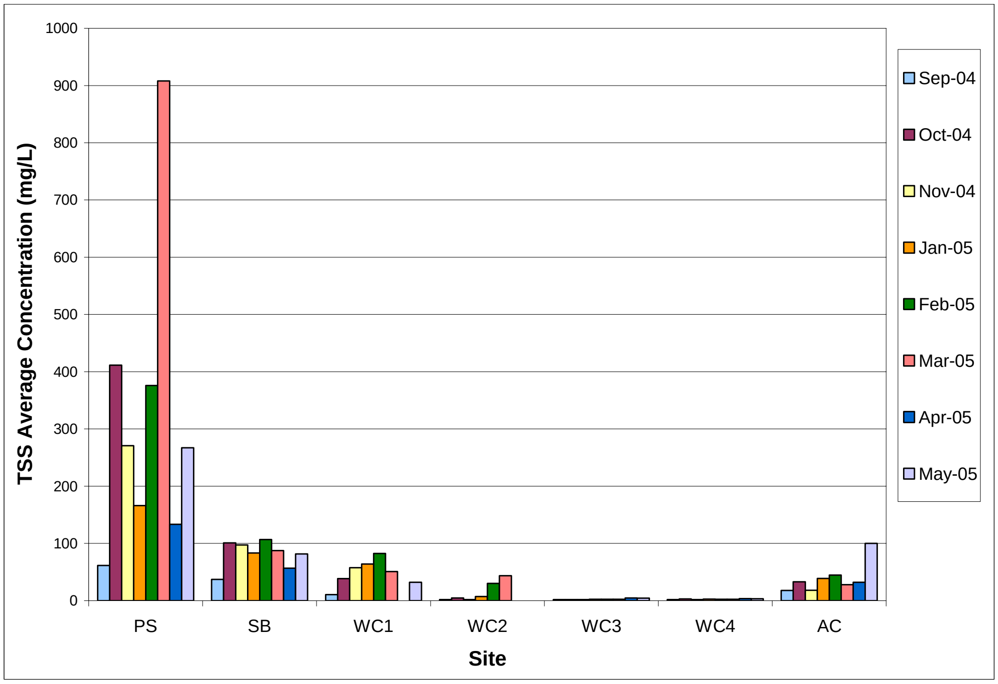

Figure D-2. Spatial variation of monthly average concentrations for TSS during the second year of operation (September 2004 – May 2005) of the field-scale wetlands.

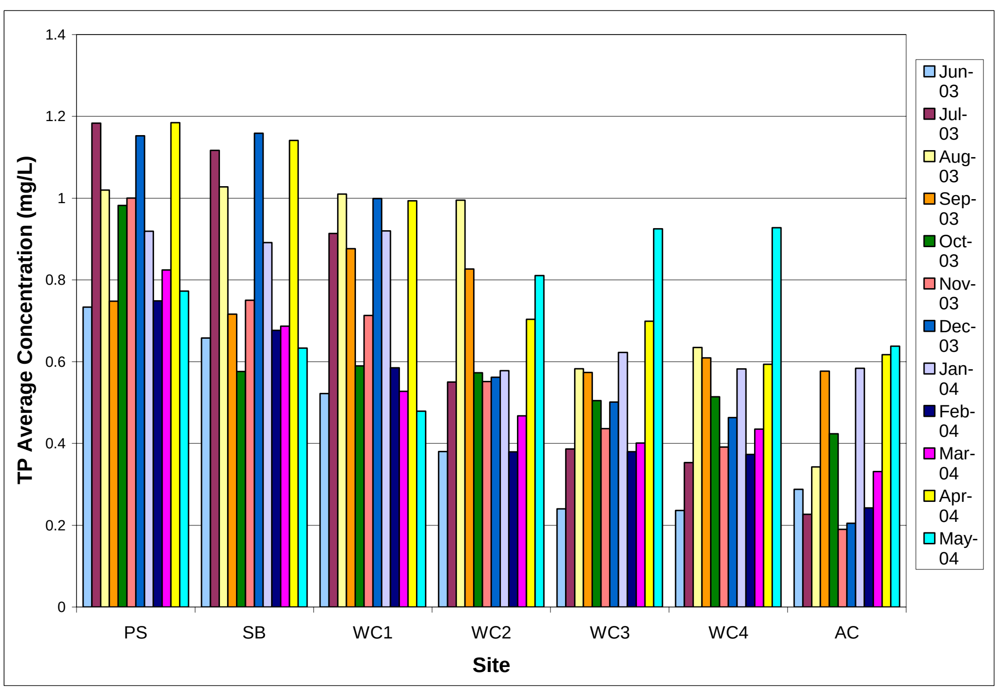

Figure D-3. Spatial variation of monthly average concentrations for TP during the first year of operation (June 2003 – May 2004) of the field-scale wetlands.

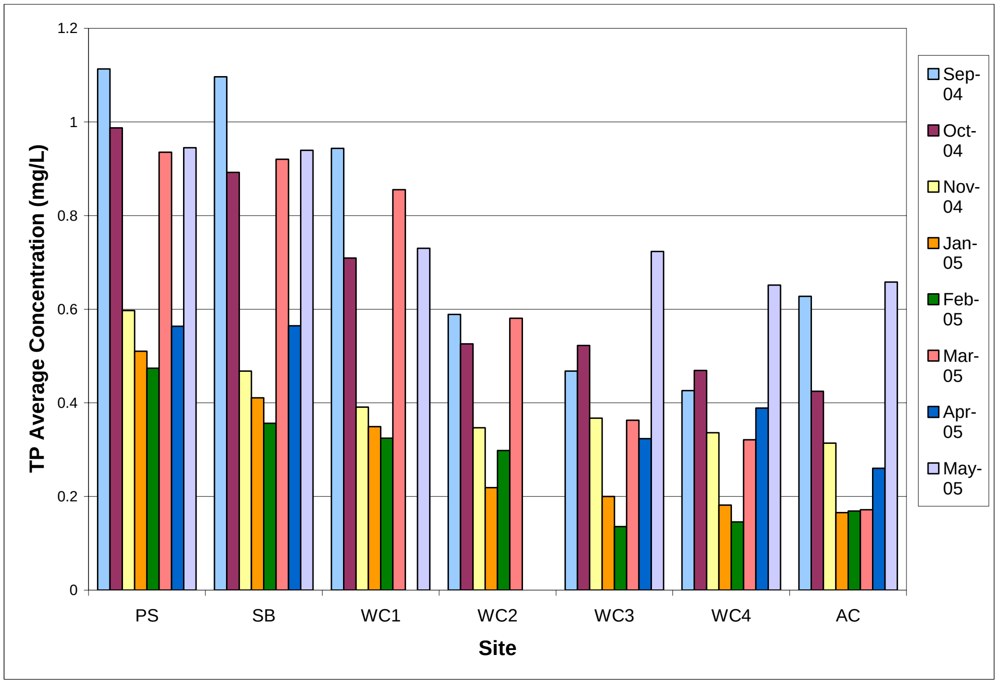

Figure D-4. Spatial variation of monthly average concentrations for TP during the second year of operation (September 2004 – May 2005) of the field-scale wetlands.

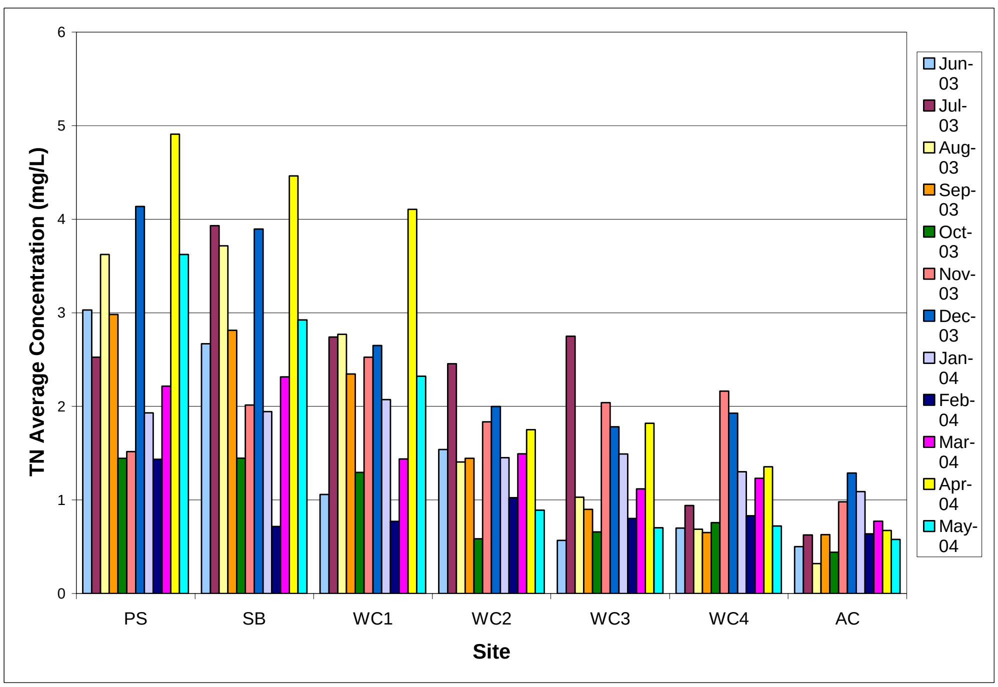

Figure D-5. Spatial variation of monthly average concentrations for TN during the first year of operation (June 2003 – May 2004) of the field-scale wetlands.

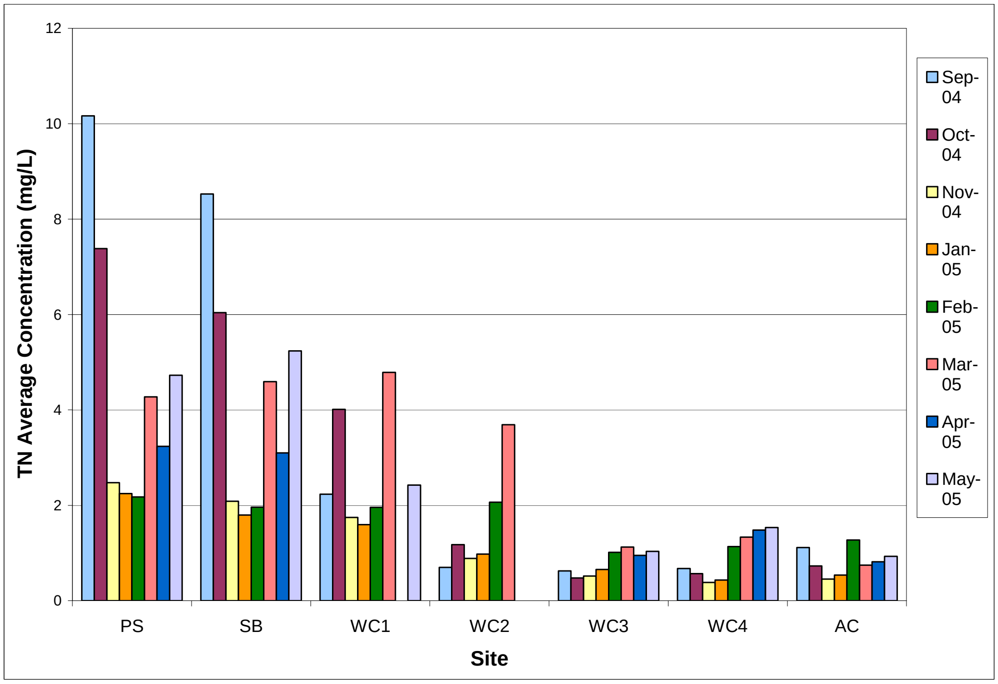

Figure D-6. Spatial variation of monthly average concentrations for TN during the second year of operation (September 2004 – May 2005) of the field-scale wetlands.

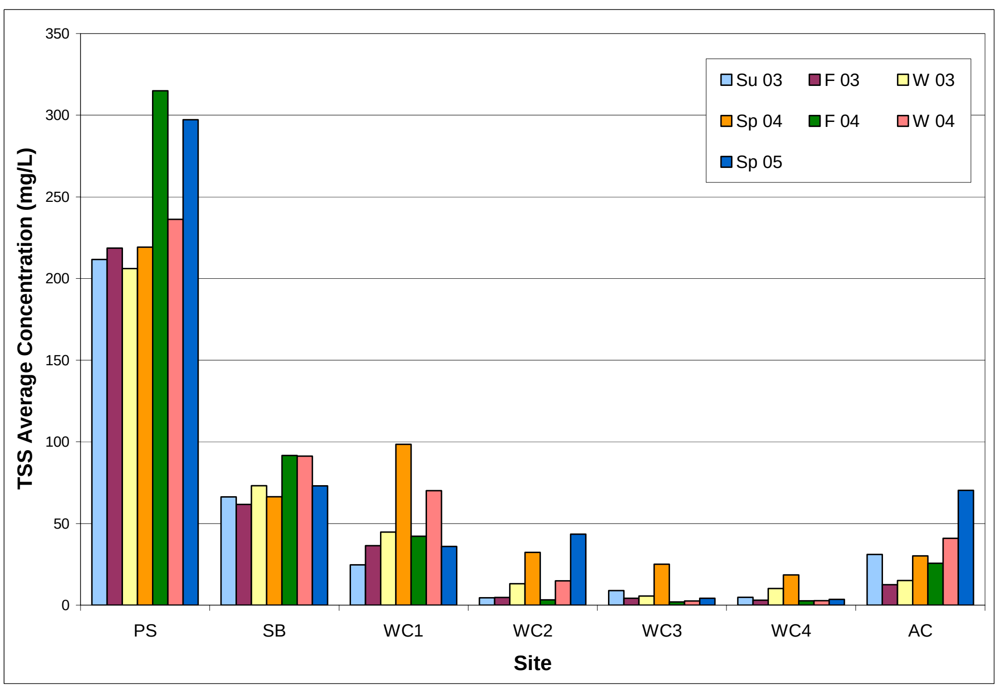

Figure D-7. Spatial variation of seasonal averages for TSS for the field-scale wetlands.

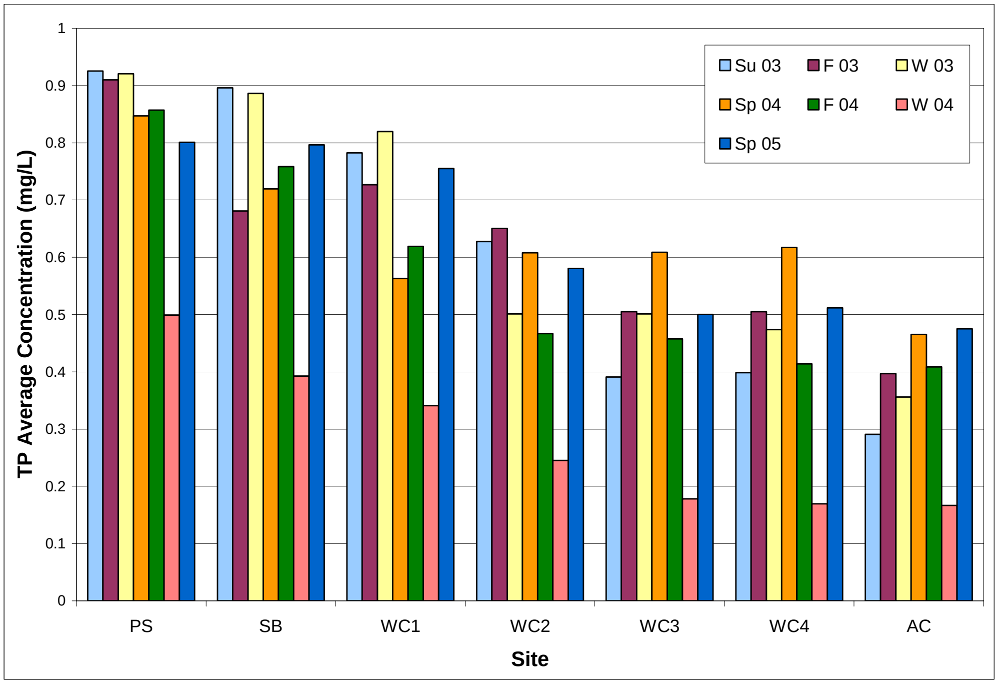

Figure D-8. Spatial variation of seasonal averages for TP for the field-scale wetlands.

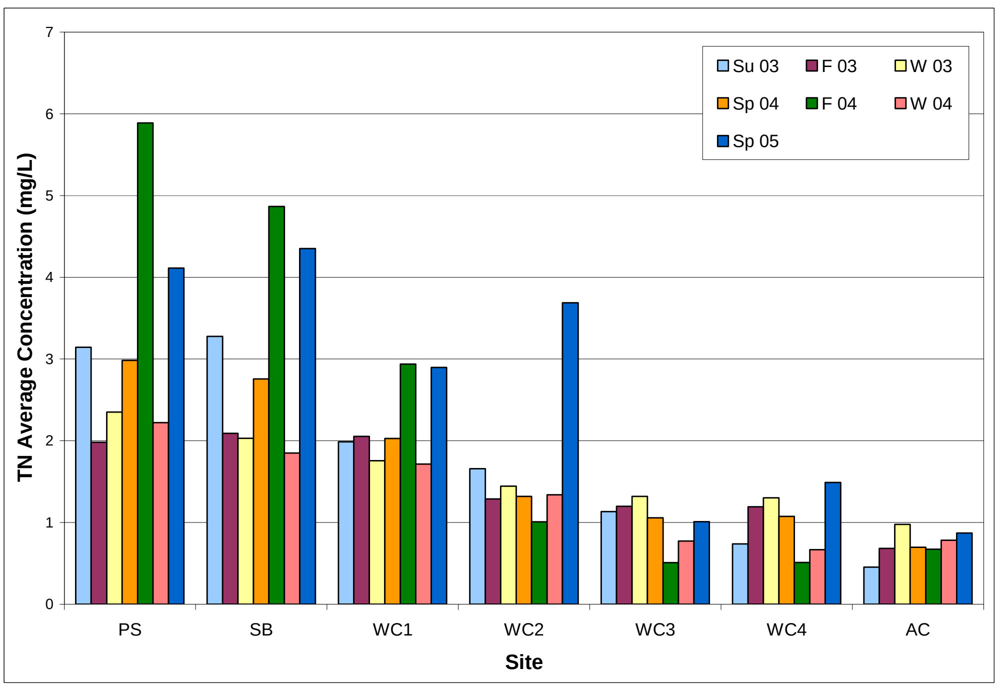

Figure D-9. Spatial variation of seasonal averages for TN for the field-scale wetlands.

APPENDIX E

VEGETATION SPECIES FOR THE FIELD-SCALE WETLAND SYSTEM

Table E-1. Vegetation species found in the field-scale wetland system during the operational period, June 2003 to May 2005.

Common Name	Scientific Name	Author
Algae		
American Germander	*Teucrium canadense* var. *canadense*	L.
American Water Willow	*Justica americana*	(L.) Vahl
Annual Aster	*Aster subulatus*	Michx.
Aquatic Milkweed	*Asclepias perennis*	Walt.
Baldwin Ironweed	*Vernonia baldwinii*	Torr.
Barnyard Grass/Millet	*Echinochloa crus-galli*	(L.) Beauv.
Black Willow	*Salix nigra*	Marsh.
Burhead	*Echinodorus rostratus*	(Nutt.) Engelm.
Crowfoot Sedge	*Carex crus-corvi*	Shuttlw. ex Kuntze
Curltop Smartweed	*Polygonum lapathifolium*	L.
Dead Eryngo	*Eryngium* sp.	
Duckweed	*Lemna* spp.	
Fall Panic Grass	*Panicum dichotomiflorum*	Michx.
Flatsedge	*Cyperus* sp.	
Grassy Arrowhead	*Sagittaria graminea*	Michx.
Jungle Rice	*Echinochloa colonum*	(L.) Link
Lanceleaf Frogfruit	*Phyla lanceolata*	(Michx.) Greene
Largespike Spikerush	*Eleocharis palustris*	(L.) R. & S.
Levenworth Eryngo	*Eryngium leavenworthii*	T. & G.
Mosquito Fern	*Azolla caroliniana*	Willd.
Obedient Plant	*Physostegia intermedia*	(Nutt.) Engelm. & Gray
Pale Dock	*Rumex altissimus*	Wood
Sedge	*Carex* sp.	
Smutgrass	*Sporobolus* spp.	
Softstem Bulrush	*Scirpus validus*	Vahl
Southern Naiad	*Najas guadalupensis*	(Spreng.) Magnus
Spiderlily	*Hymenocallis liriosme*	(Raf.) Shinners
Squarestem Spikerush	*Eleocharis quadrangulata*	(Michx.) R. & S.
Sumpweed	*Iva annua*	L.
Swamp Smartweed	*Polygonum hydropiperoides*	Michx.
Unknown sp. (grass sp.)		
Unknown sp. (Paspalum sp.)	*Paspalum* sp.	
Walter's Millet	*Echinochloa walteri*	(Pursh) Heller
Water Clover	*Marsilea* spp.	
Water Primrose	*Ludwigia peploides*	HBK.
Willow Primrose	*Ludwigia decurrens*	Walt.

Table E-2. Vegetation species found in wetland cell 1 during the operational period, June 2003 to May 2005. For type, "S" represents submerged, "F" represents floating, "E" represents emergent and "T" represents terrestrial species.

Common Name	Scientific Name	Abbr.	Type
Algae		ALG	S
American Germander	*Teucrium canadense* var. *canadense*	AG	T
American Water Willow	*Justica americana*	WW	E
Annual Aster	*Aster subulatus*	AA	T
Barnyard Grass/Millet	*Echinochloa crus-galli*	BYG	E
Burhead	*Echinodorus rostratus*	BH	T
Cocklebur	*Xanthium strumarium*	CB	T
Coontail	*Ceratophylum demersum*	CT	S
Crowfoot Sedge	*Carex crus-corvi*	CF	E
Curltop Smartweed	*Polygonum lapathifolium*	CS	E
Duckweed	*Lemna* spp.	DW	F
Fall Panic Grass	*Panicum dichotomiflorum*	FP	T
Grassy Arrowhead	*Sagittaria graminea*	GA	E
Lanceleaf Frogfruit	*Phyla lanceolata*	LF	T
Largespike Spikerush	*Eleocharis palustris*	LSS	E
Open Water		OW	
Pale Dock	*Rumex altissimus*	PD	T
Sedge	*Carex* sp.	CS	E
Smutgrass	*Sporobolus* spp.	SG	T
Softstem Bulrush	*Scirpus validus*	SSB	E
Southern Naiad	*Najas guadalupensis*	SN	S
Swamp Smartweed	*Polygonum hydropiperoides*	SSB	E
Unknown sp. (grass sp.)		?2	T
Unknown sp. (Paspalum sp.)	*Paspalum* sp.	?P	T
Walter's Millet	*Echinochloa walteri*	WM	E
Water Clover	*Marsilea* spp.	WC	E
Water Primrose	*Ludwigia peploides*	WP	F
Willow Primrose	*Ludwigia decurrens*	PW	E

Table E-3. Vegetation species found in wetland cell 2 during the operational period, June 2003 to May 2005. For type, "S" represents submerged, "F" represents floating, "E" represents emergent and "T" represents terrestrial species.

Common Name	Scientific Name	Abbr.	Type
Algae		ALG	S
Barnyard Grass/Millet	*Echinochloa crus-galli*	BYG	E
Burhead	*Echinodorus rostratus*	BH	T
Crowfoot Sedge	*Carex crus-corvi*	CF	E
Duckweed	*Lemna* spp.	DW	F
Flatsedge	*Cyperus* sp.	FS	E

Table E-3. Continued.

Common Name	Scientific Name	Abbr.	Type
Grassy Arrowhead	*Sagittaria graminea*	GA	E
Jungle Rice	*Echinochloa colunum*	JR	E
Lanceleaf Frogfruit	*Phyla lanceolata*	LF	T
Levenworth Eryngo	*Eryngium leavenworthii*	LE	T
Open Water		OW	
Pale Dock	*Rumex altissimus*	PD	T
Sedge (Carex sp.)	*Carex* sp.	CS	E
Southern Naiad	*Najas guadalupensis*	SN	S
Spiderlily	*Hymenocallis liriosme*	SL	T
Stonewort/Chara	*Chara* spp.	CH	S
Water Primrose	*Ludwigia peploides*	WP	F

Table E-4. Vegetation species found in wetland cell 3 during the operational period, June 2003 to May 2005. For type, "S" represents submerged, "F" represents floating, "E" represents emergent and "T" represents terrestrial species.

Common Name	Scientific Name	Abbr.	Type
Algae		ALG	S
American Germander	*Teucrium canadense* var. *canadense*	AG	T
Annual Aster	*Aster subulatus*	AN	T
Barnyard Grass/Millet	*Echinochloa crus-galli*	BYG	E
Burhead	*Echinodorus rostratus*	BH	T
Crowfoot Sedge	*Carex crus-corvi*	CF	E
Curltop Smartweed	*Polygonum lapathifolium*	CS	E
Dead Eryngo	*Eryngium* sp.	DE	T
Duckweed	*Lemna* spp.	DW	F
Flatsedge	*Cyperus* sp.	FS	E
Grassy Arrowhead	*Sagittaria graminea*	GA	E
Lanceleaf Frogfruit	*Phyla lanceolata*	LF	T
Largespike Spikerush	*Eleocharis palustris*	LSS	E
Levenworth Eryngo	*Eryngium leavenworthii*	LE	T
Mosquito Fern	*Azolla caroliniana*	AZ	F
Obedient Plant	*Physostegia intermedia*	OP	E
Open Water		OW	
Pale Dock	*Rumex altissimus*	PD	T
Sedge (Carex sp.)	*Carex* sp.	CS	E
Softstem Bulrush	*Scirpus validus*	SSB	E
Southern Naiad	*Najas guadalupensis*	SN	S
Spiderlily	*Hymenocallis liriosme*	SL	T
Sumpweed	*Iva annua*	SW	T
Swamp Smartweed	*Polygonum hydropiperoides*	SSB	E
Unknown sp. (Paspalum sp.)	*Paspalum* sp.	?P	T

Table E-4. Continued.

Common Name	Scientific Name	Abbr.	Type
Water Clover	*Marsilea* spp.	WC	E
Water Primrose	*Ludwigia peploides*	WP	F
Willow Primrose	*Ludwigia decurrens*	PW	E

Table E-5. Vegetation species found in wetland cell 4 during the operational period, June 2003 to May 2005. For type, “S” represents submerged, “F” represents floating, “E” represents emergent and “T” represents terrestrial species.

Common Name	Scientific Name	Abbr.	Type
Algae		ALG	S
American Water Willow	*Justica americana*	WW	E
Annual Aster	*Aster subulatus*	AA	T
Aquatic Milkweed	*Asclepias perennis*	AM	T
Baldwin Ironweed	*Vernonia baldwinii*	BI	T
Barnyard Grass/Millet	*Echinochloa crus-galli*	BYG	E
Black Willow	*Salix nigra*	BW	T
Burhead	*Echinodorus rostratus*	BH	T
Crowfoot Sedge	*Carex crus-corvi*	CF	E
Duckweed	*Lemna* spp.	DW	F
Grassy Arrowhead	*Sagittaria graminea*	GA	E
Jungle Rice	*Echinochloa colunum*	JR	E
Lanceleaf Frogfruit	*Phyla lanceolata*	LF	T
Levenworth Eryngo	*Eryngium leavenworthii*	LE	T
Open Water		OW	
Sedge (Carex sp.)	*Carex* sp.	CS	E
Softstem Bulrush	*Scirpus validus*	SSB	E
Southern Naiad	*Najas guadalupensis*	SN	S
Spiderlily	*Hymenocallis liriosme*	SL	T
Squarestem Spikerush	*Eleocharis quadrangulata*	S3	E
Sumpweed	*Iva annua*	SW	T
Swamp Smartweed	*Polygonum hydropiperoides*	SS	E
Unknown sp. (grass sp.)		?2	T
Unknown sp. (Paspalum sp.)	*Paspalum* sp.	?P	T
Water Primrose	*Ludwigia peploides*	WP	F

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